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ELEMENTS OF MECHANISM.

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THE

ELEMENTS OF MECHANISM.

DESIGNED FOR STUDENTS OF APPLIED MECHANICS.

BY

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PREFACE.

THE present Treatise has been written with the view of providing an elementary text-book on the Principles of Mechanism. The intention of the Author has been to simplify the subject as much as possible, to exhibit its prominent features, and to convey a certain amount of practical information; in doing so, he has hoped to render the work acceptable to those who are commencing the study of a difficult branch of learning.

LONDON: *Feb.* 1865.

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ELEMENTS OF MECHANISM.

INTRODUCTION.

A MACHINE may be defined to be an assemblage of moving parts, constructed for the purpose of transmitting motion or force, and of modifying, in various ways, the motion or force so transmitted.

The parts of a machine are set in motion by some moving power, which may be derived from any convenient source; and the machine itself must be constructed with reference to the character of the power from which its motion is derived.

The introduction of the steam-engine has greatly simplified the art of constructive mechanism, by rendering the source of power uniform and undeviating. The steam-engine is usually employed to give rotation to a piece of shafting, and the mechanic is then required to derive from the smooth and steady rotation of a shaft every movement which the nature of the work may demand. Thus the starting point for steam-machinery in our mills and factories is, with but few exceptions, the same throughout; and the problem of making a machine resolves itself into a question of the resolution or transfer of circular motion in every variety of manner, and subject to every possible modification.

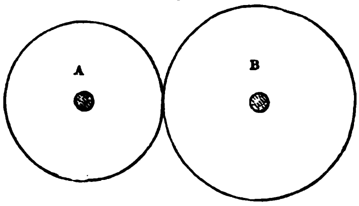
Accordingly we propose to commence with a discussion of the methods adopted for the conversion of circular into reciprocating motion; then to proceed to the reverse problem, or to examine the conversion of reciprocating into circular motion; to pass on to an enquiry into the results deduced from combinations of wheelwork in trains, giving the theory which has led to an accurate shaping of the teeth of wheels; to consider, further, some arrangements by which a moving piece may be made the recipient of two or more independent motions; and finally, to conclude by collecting and analysing certain miscellaneous contrivances which produce results of a specific and very noticeable character.

It will be necessary to premise a few general remarks and definitions.

In the transfer of motion or force from one axis to another, wheels furnished with teeth are commonly employed. The various calculations connected with the forms of teeth which are suitable for this purpose will be given hereafter; at the present time we may remark, that the most simple case of the transfer of motion from one axis to another occurs when a circular disc or plate moves another by rolling contact.

In such a case the uniform motion of the axis, A, conveys a perfectly even and uniform motion to the other axis, B. (Fig. 1.)

Fig 1.

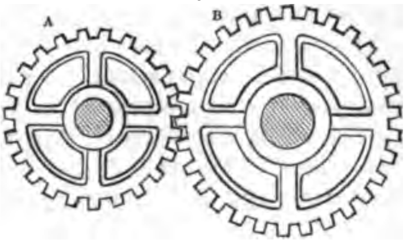


If A and B were circular plates with flat edges, and very accurately adjusted, it would be quite possible for A to move B by friction alone, the two plates rolling smoothly and evenly upon each other without any slipping of the surfaces in contact, but we could not expect A to overcome any great resistance to motion in B; or, in other words, we could

not convey force by the action of one disc upon the other.

The transmission of force being an essential condition in machinery, the discs A and B are provided with teeth, as in the annexed figure, and the mechanist endeavours so to form and shape the teeth that the motion shall be exactly the same as if one circle rolled upon another.

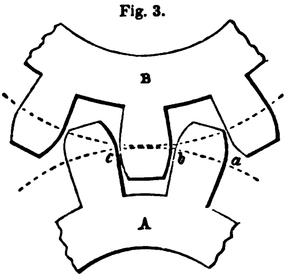
Fig. 2.



Herein consists the perfection of wheelwork, a perfectly uniform motion of the axis A is to be conveyed by means of teeth to the axis B: and the motion of B, when tested with microscopic accuracy, is to be no less even and uniform than that of A.

Since, then, it appears that the motions of A and B are exactly the same as those of two circles rolling upon each other, such imaginary circles may always be conceived to exist, and are called the *pitch circles* of the wheels in question. They are represented by the dotted lines in Fig. 3.

Fig. 3.



So much of the tooth as lies within the pitch circle is called its *root* or *flank*, and the portion beyond the pitch circle is called the *point* or *addendum*.

The *pitch of a tooth* is the space *a c* upon the pitch circle cut off by the corresponding edges of two consecutive teeth.

Spur wheels are represented in Fig. 2, and are those in which the teeth project radially along the circumference.

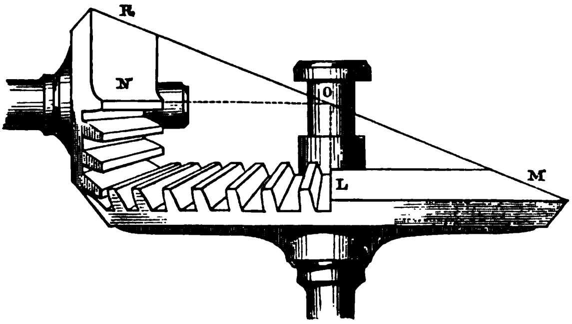
In a *face wheel*, cogs or pins, acting as teeth, are fastened

perpendicularly to the plane of the wheel; in a *crown wheel* the teeth are cut upon the edge of a circular band; and *annular wheels* have the teeth formed upon the inside of an annulus or ring, instead of upon the outer circumference.

A straight bar provided with teeth is called a *rack*, and a wheel with a small number of teeth is termed a *pinion*.

The spur wheels, before described, are suited to convey motion only between parallel axes; it often happens, however, that the axes concerned in any movement are not parallel, and as a consequence they may, or may not, meet in a point. If the axes do not intersect we proceed by successive steps, and continually introduce intermediate

Fig. 4.



intersecting axes, and thus we are led to the use of inclined wheels whose axes meet each other, and which are known as *Bevil wheels*. (Fig. 4.)

It is easily proved in Geometry that two right cones which have a common vertex will roll upon each other, and the same would be true of the frustra of two cones such as L M and N R, which are represented as having a common vertex in the point O.

The rolling of the cones will allow us to consider any pair of circles in contact and perpendicular to the respective axes as the pitch circles of the frustra, and teeth may

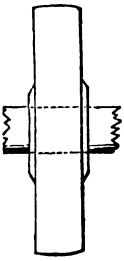
accordingly be shaped upon them so as to produce the same even motion as that which exists in the case of spur wheels.

Equal bevil wheels whose axes are at right angles are termed *mitre wheels.*

It is sometimes convenient that the axes of the bevil wheels should pass close to each other without intersecting; the teeth have then a twisted form, and the wheels are known as *skew bevils.*

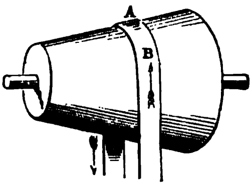
Belts or *bands* are much used in machinery, in order to communicate motion between two axes at a distance from each other. In this case an endless band is stretched over the circumference of a disc or pulley upon each axis, and the motion is the same as if the discs rolled directly upon each other. (Fig. 5.)

Fig. 5.



The form of each pulley is slightly convex, and the strap will then remain upon the discs. The reason of this curious fact will be apparent if we examine the case of a tight belt running upon a revolving conical pulley. The belt embraces the surface of the cone, and thus becomes bent into the form A B, the portion B being somewhat nearer to the base of the cone than the portion A. (Fig. 6.)

Fig. 6.



The cone, during its revolution, exerts an effort to carry B onward in a circle parallel to its base, and the consequence is that the belt tends to remain upon the slant surface of the cone, and to rise higher rather than to slip off.

The *fast and loose pulley* is an adjunct of the driving belt. It consists of two pulleys, whereof one is keyed to the shaft to which motion is to be conveyed, and the other rides loose upon it; when the strap is shifted from the loose to the fastened pulley the shaft will begin to rotate,

otherwise it remains at rest, the loose pulley alone turning round.

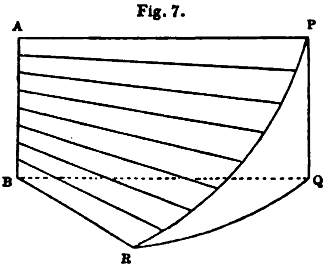
The band is shifted by a fork, which is made to press laterally upon its *advancing* side.

The advancing portion of a band must always lie in the plane of the pulley round which it is wrapped, but the retreating portion may be pulled on one side without causing the strap to leave the pulley. By observing this principle, a band may be employed to communicate motion between two axes which are not parallel to each other.

After toothed wheels, the screw plays the most important part in mechanical appliances, and indeed it is difficult to over-estimate its value or utility. The screw bolt and nut are used to unite the various parts of machinery in close and firm contact, and are peculiarly fitted for that purpose; then, again, the screw is employed in the slide rest and in the planing machine to give a smooth and even longitudinal motion, the same purpose for which it aids the astronomer in measuring the last minute intervals which are recognisable in the telescope. In the screw press we rely upon it to transmit force, we use it in screw piles to obtain a firm foundation for piers or light-houses, and as a propeller for ships it has given a new element of strength and power to our navy.

The definitions relating to the screw are the following:—

Fig. 7.



If a horizontal line A P, which always passes through a fixed vertical line, be made to revolve uniformly in one direction, and at the same time to ascend or descend with a uniform velocity, it will trace out a *screw surface* A P R B, in the manner indicated in Fig. 7.

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The points of intersection of this generating line with any circular cylinder whose axis coincides with A B, will form a *screw thread*, P R, upon the surface of the cylinder.

The *screw thread* used in machinery is a projecting rim of a certain definite form, running round the cylinder, and obeying the same geometrical law as the ideal thread just described.

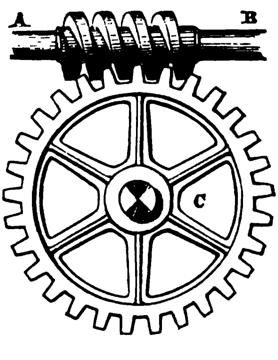
The *pitch of a screw* is the space along A B, through which the generating line moves in completing one entire revolution, but in practice the pitch of a screw bolt is usually estimated by observing the number of ridges which occur in an inch of its length; thus we speak of a screw of one-eighth of an inch pitch as being a screw with eight threads to the inch.

Also A B is called the *length* of the screw surface A P R B, and the angle P R Q represents the *angle* of the screw.

In the diagram, A P is shown as describing a *right-handed* screw; if it revolved in the opposite direction during its descent, it would describe a *left-handed* screw.

If a single thread were wound evenly round a cylinder, and the path of the thread marked out, we should have a *single-threaded* screw; whereas, if two parallel threads were wound on side by side, we should obtain a *double-threaded* screw, of which A B in Fig. 8 is an example. The object of increasing the number of threads is to fill up the space which would be unoccupied if a fine thread of rapid pitch were traced upon a bolt.

Fig. 8.



A *worm wheel* is a wheel furnished with teeth set obliquely upon its rim, and so shaped as to be capable of engaging with the thread of a screw; the revolution of the

endless screw or worm A B will then impart rotation to the wheel C (Fig. 8); and since the endless screw, as represented, is a double-threaded screw, the wheel will advance through the space of two teeth upon each revolution of A B. This reduction of velocity causes the combination to be most valuable as a simple means of obtaining mechanical advantage.

The number of threads upon the screw determines the number of teeth by which the wheel will advance during each revolution of A B.

In the transmission of force the screw is always employed to drive the wheel, and necessarily so, because the friction would prevent the possibility of driving the screw by means of the wheel, even if the loss of power were disregarded; but in very light mechanism, where the friction is insensible, the wheel may drive the screw, and then the screw is frequently connected with a revolving fly, and serves to regulate the rate at which a train of wheels terminating in the worm wheel may run round.

The term *axis* denotes the central line of a cylinder, and is a mathematical phrase: an engineer distinguishes a heavy cylindrical piece of metal as *shafting*, or a *shaft*, and designates smaller cylindrical bars as *spindles*; a wheelwright speaks of the *axle* of a wheel, and a watchmaker calls the same thing an *arbor*.

Of two moving pieces, that which transmits motion is termed the *driver*, and that which receives it is the *follower*.

Gearing and *Gear* are the words used to indicate the combination of any number of parts in a machine which are employed for a common object.

Toothed wheels are said to be *in gear* when they are capable of moving each other, and *out of gear* when they are shifted into a position where the teeth cease to act.

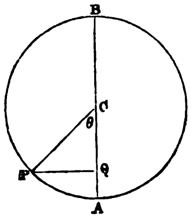
CHAPTER I.

ON THE CONVERSION OF CIRCULAR INTO RECIPROCATING MOTION.

Art. 1. The most simple case of motion is that of a point describing a straight line with a uniform velocity. Whenever a point deviates from a rectilinear path, and describes a plane curve of any form, it must be the subject of two independent movements in lines at right angles to each other.

Thus, let a point move in a circular path, A P B, with a uniform velocity, then it is evident that the point, P, while describing the arc A P, has been the subject of two rectilinear movements, one from A to Q, in the direction of the diameter A B, the other from Q to P, in a perpendicular direction. (Fig. 9.)

Fig. 9.



In other words, circular motion is of a compound character, and capable of resolution into its elements; if it be thus resolved, and if one equivalent be suppressed, so that the motion of Q is substituted for that of P, we obtain the fundamental case of the conversion of circular into reciprocating motion.

2. Let C A $= a$, P C A $= \theta$;

then A Q $=$ A C $-$ C Q $= a - a \cos\theta = a(1 - \cos\theta)$; which equation gives the analytical representation of motion of this character.

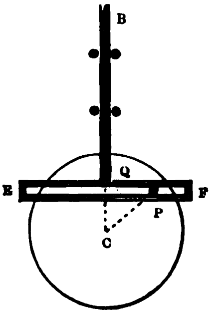
The velocity of the point Q being expressed by the limiting value of the ratio of the small increase of A Q to that of θ when the latter is indefinitely diminished, the student

will easily discover for himself that in the present instance this ratio becomes equal to the quantity (a sin θ); hence as the point P moves uniformly round the circumference, the point Q will oscillate through the line A B with a velocity which is not uniform, but which varies as the sine of θ.

Moreover, the point Q begins to move very slowly along A B on starting from A, and again also upon approaching B, its greatest velocity occurring about the centre of its path; if, therefore, the motion of Q were compared with that of a point, R, supposed to describe A B in the same time with a uniform velocity, it would be found that Q and R coincided in the points A, C, and B; but that R was in advance of Q between A and C, and that Q preceded R from C to B.

3. The motion of Q may be derived from that of P by the following contrivance:—

Fig. 10.



Let P represent a small pin set in a circular plate which is moveable about C as a centre of motion, and let the pin work in a groove, E F, whose direction is at right angles to that of the sliding bar, Q B. (Fig. 10.)

Of the two equivalents which combine to produce the circular motion of P, that which occurs in the direction F E is rendered inoperative, and the whole of the other equivalent is imparted to the sliding bar; in this way, then, the bar rises and falls as the disc rotates upon its centre.

4. We proceed now to analyse the conversion of circular into reciprocating motion by means of the *crank and connecting rod.*

A crank is merely a lever or bar moveable about a centre at one end, and capable of being turned round by a force applied at the other end; in this form it has been used from

the earliest times as a handle to turn a wheel. When the crank is attached by a connecting rod to some reciprocating piece, it furnishes a combination which is extremely useful in machinery.

In the next chapter we shall see that the crank and connecting rod is one of the principal contrivances for converting reciprocating into circular motion; the student will understand that any such distinction as to the effect of the contrivance is one of classification only, regard being had to the direction in which the moving force travels. The arrangement is often used under both aspects in one and the same machine; as in a marine engine, where the piston in the steam-cylinder actuates the paddle-shaft by means of a crank and a connecting rod, and the motion is then carried on by the same device to the bucket or piston of the air-pump.

It was in the year 1769 that James Watt published his invention of "A method of lessening the consumption of Steam and Fuel in Fire-Engines," the main feature of which was the condensation of the steam in a vessel distinct from the steam-cylinder. The steam-engine was at that time called a fire-engine, and was used exclusively in pumping water out of mines; the steam piston and the pump rods were suspended by chains from either end of a heavy beam centred upon an axis, the action of the steam caused a pull in one direction only, and the pump rods being raised by the agency of the steam were afterwards allowed to descend by their own weight.

In this shape the steam-engine was entirely unfitted for actuating machinery, and it was not until after the impulse given by Watt's invention was beginning to be felt that it became apparent that the expansive force of steam could be made available as a source of power in driving the machinery of mills.

While Watt was occupied with this great problem, which eventually he fully solved, it happened that one James

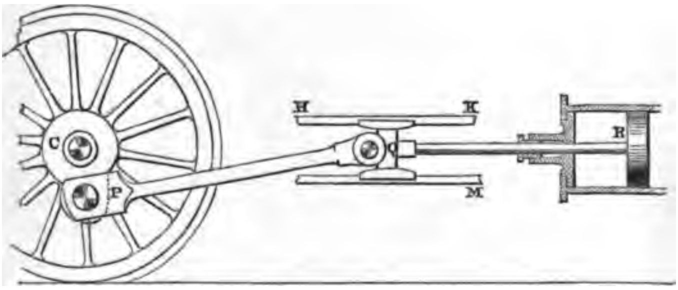
Pickard, of Birmingham, in the year 1780, took out a patent for a "new invented method of applying steam or fire engines to the turning of wheels," in which he proposed to connect the great working beam of the engine with a crank upon the shaft of a wheel by means of a spear or connecting rod, jointed at its extremities to the beam and crank respectively.

It is probable that Watt had foreseen this application of the crank as early as the year 1778, and had intended to apply the combination as a means of carrying on the power from the end of the working beam to the fly-wheel; being forestalled, however, by the patentee, he did not dispute the invention, and contented himself with patenting certain other methods of obtaining a like result, among which will be found the sun and planet wheels described in chapter 5.

This latter invention served his purpose until the patent for the crank had expired, and then it was that the more simple arrangement which we are now about to discuss came into general use.

5. The manner of employing the crank and connecting

Fig. 11.

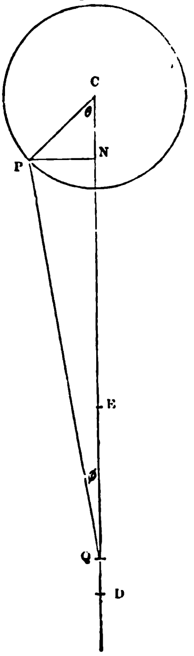


rod in the locomotive engine is shown in Fig. 11. The crank C P is made a part of the driving wheel of the engine,

the connecting rod P Q is attached to the end of the piston rod Q R, and the end Q is constrained to move in a horizontal line by means of the guides H K, L M. The contrivance here referred to belongs properly to the second chapter, as we propose at present to confine our attention to the conversion of circular into reciprocating motion.

6. The object of the following analysis is to determine the relative positions of the crank and reciprocating piece during the motion.

Fig. 12.



Here C P represents an arm or *crank* centred at C (Fig. 12), and connected by means of a link or *connecting rod*, P Q, with a point Q, which is constrained to move in the line C E D.

Draw P N $\perp^r$ C D, and let C P $= a$, P Q $= b$, P C Q $= \theta$, P Q C $= \phi$;

then C Q = C N + N Q

$= a \cos\theta + b\cos\phi$;

also $\dfrac{a}{b} = \dfrac{\sin\phi}{\sin\theta}$ $\therefore \sin\phi = \dfrac{a}{b}\sin\theta$

and $\cos\phi = \sqrt{1 - \dfrac{a^2\sin^2\theta}{b^2}}$

$\therefore$ C Q $= a\cos\theta + \sqrt{b^2 - a^2\sin^2\theta}$;

whence the position of Q is known at any period of the motion of C P.

Cor. 1. Let $\theta = o$ $\therefore$ C D $= a + b$

$\theta = \pi$ $\therefore$ C E $= -a + b$

whence D E = C D − C E $= 2a$.

The space D E is called *the throw of the crank.*

Cor. 2. Again D Q = C D − C Q

$= a + b - a\cos\theta - b\cos\phi$

$= a(1 - \cos\theta) + b(1 - \cos\phi)$;

or the motion of Q differs from that in the last example, by the addition of the movement represented by $b(1 - \cos\phi)$; it is compounded of the resolved parts of two circular

motions, the one being that due to the motion of P in a complete circle round C, and the other resulting from the motion of P through a part of a circle whose radius is P Q.

It follows that when D C P is a right angle, Q is not in the middle of its stroke, but that D Q is greater than E Q.

Ex. Let $\left.\begin{array}{l}\text{C P} = 10 \text{ inches} \\ \text{P Q} = \;\,5 \text{ feet}\end{array}\right\}$ as in the case of the engine sketched in Fig. 11.

$$\text{Let } \theta = 90\text{; then } \sin\phi = \frac{\text{C P}}{\text{P Q}} = \frac{10}{60} = \frac{1}{6}$$

$$\therefore \cos\phi = \sqrt{1 - \frac{1}{36}} = \sqrt{\frac{35}{36}} = \frac{1}{6}\sqrt{35}.$$

$$\begin{aligned}\text{And D Q} &= a(1 - \cos\theta) + b(1 - \cos\phi) \\ &= 10 + 60\left(1 - \frac{1}{6}\sqrt{35}\right) \\ &= 10 + \cdot 84 \text{ nearly,}\end{aligned}$$

or Q is nearly six-sevenths of an inch in advance of the centre of its path when the crank has made a quarter of a revolution from the line C D.

This inequality in the motion of Q, which is caused by the shortness of the connecting rod, produces a sensible effect in the working of direct acting engines, and tends to make the mean pressure of the steam greater in the up stroke, where the piston is gaining in its motion, than in the down stroke, where it is lagging behind.

Cor. 3. If the crank could be prolonged until it became infinite, we should have $\phi = 0$, $\cos\phi = 1$, and the travel of Q represented by the equation, D Q $= a(1 - \cos\theta)$.

A crank with a connecting rod of infinite length is an imaginary creation, but we shall presently see that an equivalent motion may be obtained in various ways, and we have indeed already met with it in **Art. 3**.

7. The *Eccentric Circle* supplies a ready method of obtaining a crank and link.

Let P (Fig. 13) be the centre of a circular plate which is

movable about C as a centre of motion, Q D a bar capable of sliding in a vertical line through C. As the circle re-

Fig. 13.

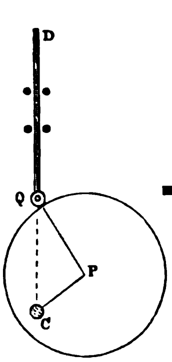


Fig. 14.

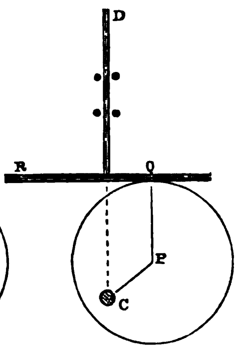
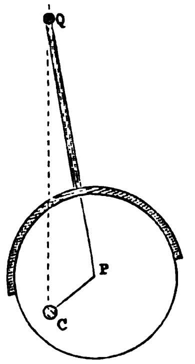


Fig. 15.



volves, P Q remains constant, and the motion is that of a crank, C P, with a link, P Q.

If the roller at Q be replaced by a bar Q R at right angles to D C (Fig. 14), we have P Q parallel to itself in all positions, and recur to the crank with an infinite link.

If the roller at Q be replaced by a portion of a circular hoop which embraces the plate (Fig. 15) and a point Q in the bar be constrained to move always in the line C D, we shall extend the link beyond the limits of the circular plate, and derive a crank, C P, with an arm, P Q.

8. We select the following example to show the use of an eccentric circle under the form represented in Fig. 14.

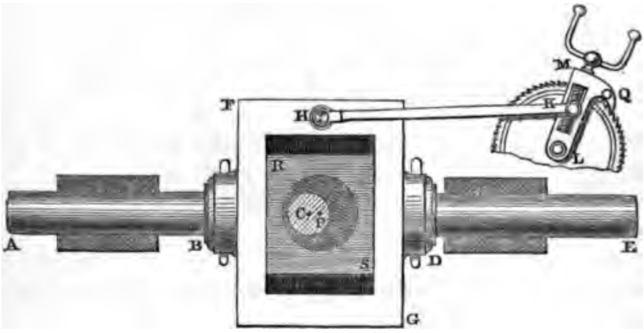
In Mr. Anderson's machine for compressing elongated rifle bullets, there are punches fixed at the two ends of a strong massive rod, to which a reciprocating motion in a horizontal line is imparted, and a piece of lead is compressed into the required form at each end alternately.

In Fig. 16 the small circle centred at C represents in section a shaft caused to rotate by the power of an engine,

upon this shaft a short cylindrical block is forged so as to form part of it, and is afterwards accurately turned into the form of a circular cylinder, whose axis passes through P upon one side of the original axis.

A rectangular brass block, R S, is bored out to fit the larger cylinder and slides in the rectangular frame F G, to which

Fig. 16.



the cylindrical pieces A B, D E are attached; the whole is put together in the manner shown, and it requires very little effort to understand that the rotation of the eccentric cylinder round an axis through C imparts to R S simultaneous movements in a horizontal and vertical direction, whereof one is inoperative and the other is communicated directly to F G, and therefore to the rods carrying the punches. Thus A B and C D are made to oscillate in the guides indicated in the sketch.

The contrivance of the wheel at the right hand will be explained in Chapter 2.

9. The crank with an infinite link also appears under the guise of a *swash plate.*

Here a circular plate, E F (Fig. 17), is set obliquely upon an axis, A C, and by its rotation drives a sliding bar P Q, whose direction is parallel to A C.

A small roller at Q relieves the friction between the end of the bar and the plate.

In Fig. 18, E and F represent the highest and lowest

Fig. 17.

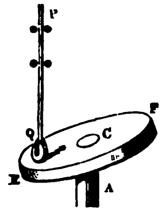
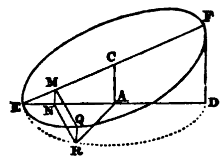


Fig. 18.



points of the path of Q, and the circle E R D is the projection of this path upon a plane $\perp^r$ to the axis A C.

Draw Q M $\perp^r$ to E F, Q R $\perp^r$ to the plane E R D, and R N $\perp^r$ to E D.

Join M N, and suppose the axis to rotate through an angle E A R $= \theta$, and thus to carry Q through the vertical space R Q.

Then
$$\text{R Q} = \text{M N} = \text{A C} \times \frac{\text{E N}}{\text{E A}}$$
$$= \text{A C}\left(\frac{\text{E A} - \text{A N}}{\text{E A}}\right) = \text{A C}\left(1 - \frac{\text{A N}}{\text{A R}}\right)$$
$$= \text{A C}\,(1 - \cos\theta);$$

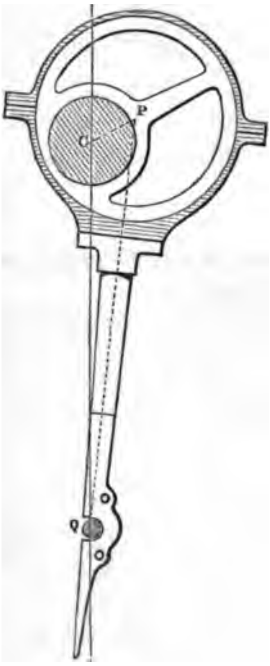
or the motion is that of a crank A C with an infinite link.

10. The form which the eccentric circle usually takes in practice is deduced at once from the arrangement in Fig. 15. A circular plate is completely encircled by a hoop, to which a bar is attached: this bar always points to P, the centre of the plate, and its extremity drives a pin Q, which is constrained to move in the line C Q. (Fig. 19.)

The plate is moveable about a centre of motion at C, and we have already explained that P Q remains constant during each revolution of the plate, or that the resulting motion impressed upon Q is that due to a crank, C P, and a link, P Q.

We should remark that P, the centre of the plate in question, may be brought as near as we please to C, the centre of the shaft, and that the throw of the eccentric may be reduced accordingly; but that we are limited in the other direction, for the shaft must be kept within the boundary of the plate, and the plate itself must not be inconveniently large, — considerations which are sufficient to prevent our increasing C P in any great degree.

Fig. 19.



The eccentric circle may also be regarded as a simple form of *cam* (see Art. 18), but we have examined it here on account of its being identical in principle with the crank and connecting rod.

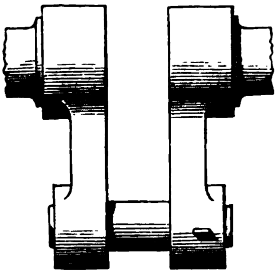
The object of the complete hoop is to drive Q in alternate directions. In some cases Q is brought back by a spring, and then only half the hoop is required; an instance occurs in modern forging machines, where the motion is very small and rapid.

11. On referring back to Fig. 11, it will be seen that the crank and connecting rod labours under the disadvantage of entailing a division of the shaft whenever it is required to place the crank anywhere except at one end.

Whenever a crank is required in some intermediate portion of an axle or shaft, the axle is *cranked* in the manner shown in Fig. 20, or it is divided, and the two cranks or arms are connected by a pin. These cranks

and the pin are frequently forged in one solid mass upon the shaft, and shaped afterwards by the machinery of the workshop.

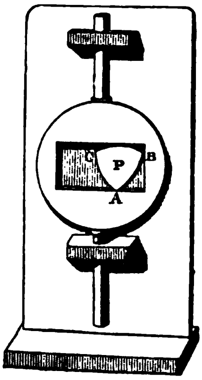
Fig. 20.



The great value of the eccentric arises from the circumstance that it enables us to derive the motion, which would be given by a crank, from any part of a shaft without the necessity of subdividing it; this is particularly noticeable in the mechanism of the steam-engine, where the crank of small throw which is required for moving the steam slide-valves, is almost invariably furnished by the aid of an eccentric.

12. An intermittent motion may be obtained by placing a loop at the point where the eccentric bar engages the pin; if such a loop be provided it can be seen that the pin Q can only move when one end of the loop takes it up.

Fig. 21.



But an intermittent motion may be obtained in a much better manner by a movement adapted for working the valves of a steam-engine.

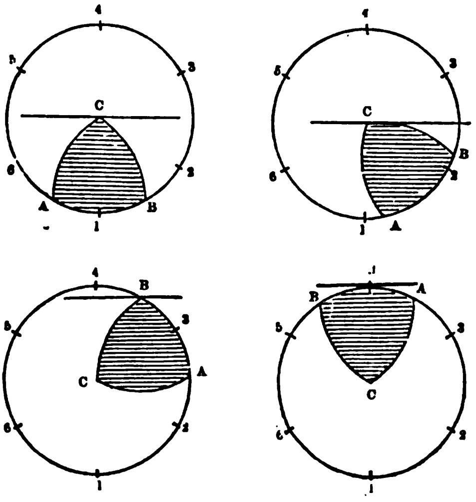
We observe that if any portion of the plate in Art. 7 be shaped in the form of a circle round C, such portion will have no power of moving the sliding bar.

Let the pin P assume the form of a circular equilateral triangle, C A B, formed by three circular arcs, whose centres are in A, B, and C, respectively, and let it be embraced by a rectangular frame attached to a sliding rod. (Fig. 21.)

As O A B revolves round the point C, the portion C B will raise the plate; the point B will next come into action, and will raise the plate still higher; the upper edge of the groove will then continue for a time upon the curved surface A B, which is a circular arc described about C as a centre, and here the motion will cease; the plate will next begin to fall, will descend as it rose, an interval of rest will succeed, and thus we shall produce an intermittent movement, which may be analysed as follows:—

Suppose the circle described by B to be divided into six equal parts, at the points numbered 1, 2, 3, 4, 5, 6.

Fig. 22.



As B moves from 1 to 2, the frame remains at rest; from 2 to 3 the arc C B drives the frame, and the motion is that of a crank C B with an infinite link; from 3 to 4 the point B drives, and the motion is that of a crank C B with an infinite link; i.e. the motion from 3 to 4 is the same as that from 2 to 3, except that it is decreasing in velocity instead of increasing.

From 4 to 5 there is rest, then an increase of motion from 5 to 6, and finally a decrease to zero as B passes through the arc 6 to 1 and completes an entire revolution.

13. We have hitherto confined our attention to one simple example in the geometry of motion: we shall now extend our view of the subject, and shall consider the driver to possess circular motion whenever it rotates continuously upon a fixed centre or axis; and in order to generalise still further, we shall suppose the reciprocating motion to be either rectilinear or circular; we shall in this manner be enabled to bring under one point of view a great variety of useful mechanical contrivances.

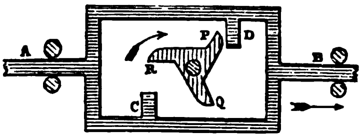
14. Circular may be converted into reciprocating motion by the aid of *escapements.*

An *escapement* consists of a wheel fitted with teeth which are made to act upon two distinct pieces or *pallets* attached to a reciprocating frame, and it is arranged that when one tooth escapes, or ceases to drive, the other shall commence its action.

One of the most ancient forms is the following:—

A sliding frame, A B, is furnished with two projecting pieces at C and D, and within it is centred a wheel possessing three teeth, P, Q, and R, which tends always to turn in the direction indicated by the arrow. (Fig. 23.)

Fig. 23.

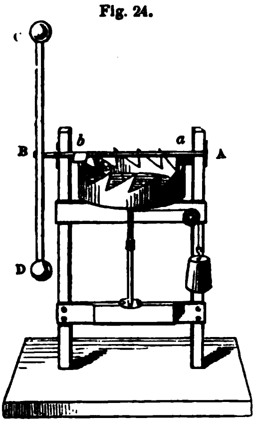


The upper tooth, P, is represented as pressing upon the projection D, and driving the frame to the right hand: when the tooth P escapes, the action of Q commences upon the other side of the frame, and the projection C is driven to the left hand. Thus the rotation of the wheel causes a reciprocating movement in the sliding piece, A B.

It is clear that the wheel must have 1, 3, 5, or some odd number of teeth upon its circumference.

15. The crown wheel escapement was invented for the earliest clock of which we possess any record.

Fig. 24.



The form of the wheel is that of a circular band, with large saw-shaped teeth cut upon one edge; the vibrating axis A B (Fig. 24), carries two flat pieces of steel, *a*, *b*, called pallets, which project from the axis in directions at right angles to each other, and engage alternately with teeth upon the opposite sides of the wheel. Suppose the wheel to turn in the direction towards which the teeth incline, and let one of its teeth encounter the pallet *b* and push it out of the way; as soon as *b* escapes, a tooth on the opposite side meets the pallet *a* and tends to bring the axis A B back again: thus a reciprocating action is set up, which will be very rapid unless A B is provided with a heavy arm, C D, at right angles to itself. Such an arm possesses *inertia*, so that its motion cannot be suddenly checked and reversed, and a recoil action is set up which materially subtracts from the utility of this contrivance. For it will be seen that the vibration of C D cannot be made to cease suddenly, and that the wheel must of necessity give way and recoil at the first instant of each engagement between a tooth and its corresponding pallet.

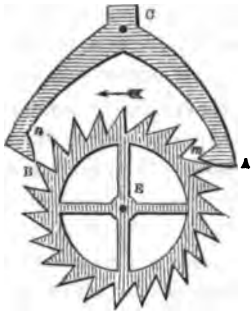
The more heavily C D is loaded at a distance from the axis the more slowly will the escapement work, and the greater will be the amount of the recoil.

Here we have an invention which has done good service to mankind. It was used in the first clock that was ever made: then it became an essential part of all watches, and now finally it is everywhere found in the kitchen-jack for roasting meat.

The principle of this escapement is precisely the same as that of the preceding one; the number of teeth in the wheel must therefore be odd, or otherwise the axis A B must be set upon one side of the centre of the crown wheel.

16. The *Anchor Escapement* was invented by Dr. Hooke, and is almost universally adopted in the mechanism of pendulum clocks.

Fig. 25.



A wheel centred at E is provided with a number of teeth, and tends always to turn in the direction indicated by the arrow. (Fig. 25.)

A portion of this wheel is embraced by an anchor, A C B, centred at C, the extreme ends of which are formed into pallets, A *m* and B *n*: these pallets may be flat or slightly convex, but they are subject to the condition that the perpendicular to A *m* shall pass below E, and the perpendicular to B *n* shall pass between C and E. The point of a tooth is represented as escaping from the pallet B *n* after driving the anchor to the left hand; as soon as this tooth has escaped, another meets A *m*, and drives the anchor to the right hand, and thus the wheel can only proceed by causing a vibratory motion in the anchor, A C B.

The rapidity of this vibration may be very great, or it may be reduced by connecting the anchor with a much heavier body, such as the pendulum of a clock.

There is the same recoil experienced upon each swing of the pendulum as that which we noticed in the last article, and the contrivance is generally known as the 'Recoil Escapement.'

The exact character of the action which takes place between the pendulum of a clock and the scape wheel has been the subject of a long and interesting mathematical investigation: it is foreign to our purpose to discuss it here, but we may state generally the nature of the problem.

The going part of a clock consists of a train of wheels tending to move under the action of a weight or spring: if the last wheel of the train were left to itself, it would spin round with great velocity, and we should fail in obtaining any measure of time.

The escapement is one part of a contrivance for regulating the velocity of the train of wheels, but the escapement alone is not sufficient; we require further a vibrating body possessing *inertia*, the motion of which cannot be suddenly stopped or reversed.

Such a body is found in the pendulum, and a very intricate mutual action exists between the pendulum and the scape wheel. The function of the pendulum is to regulate and determine the periods and amount of onward motion in the scape wheel, whereas the office of the wheel is to impart such an impulse to the pendulum at each period of this onward movement as may serve to maintain its swing unimpaired, and may cause it to move with the same mathematical precision which would characterise the vibrations of a body swinging *in vacuo*, and uninfluenced by any disturbing causes.

17. The teeth in the wheel are sometimes replaced by

Fig. 26.

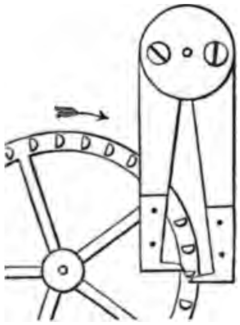
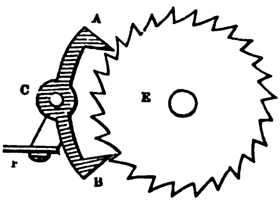


Fig. 27.



pins, in which case the form of the anchor may be so altered that the action shall take place upon one side of the wheel, as shown in Fig. 26.

In a printing telegraph instrument the recoil escapement has been employed to control the rapidity of motion in a train of wheels, and the number of vibrations of the anchor are appreciated by listening to the musical note which it imparts to a vibrating spring.

The anchor A C B (Fig. 27) is centred at C, and vibrates rapidly as the scape wheel E revolves; a strip of metal F carries on the oscillation to a steel spring which gives the note, and the velocity of the train can be regulated by an adjustable weight attached to the spring.

Again, the same escapement forms part of the mechanism of an alarum clock, a hammer is attached by a bar to the anchor, and blows are struck upon the bell of the clock in rapid succession, as the scape wheel runs round.

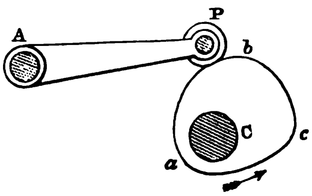
18. Circular may be converted into reciprocating motion by the aid of *cams*.

The term 'cam' is applied to a curved plate or groove which communicates motion to another piece by action of its curved edge.

Such a plate is shown in Fig. 28, and, as an illustration, we shall suppose that the portions *a b*, *c a* are any given curves, and that *b c* is a portion of a circle described about the centre of motion.

It is easy to understand, that as the cam rotates in the direction of the arrow, the roller P at the end of the lever A P will be raised gradually by the curved portion *a b*, will be held at rest while *b c* passes underneath it, and, finally, will be allowed to fall by the action of *c a*.

Fig. 28.

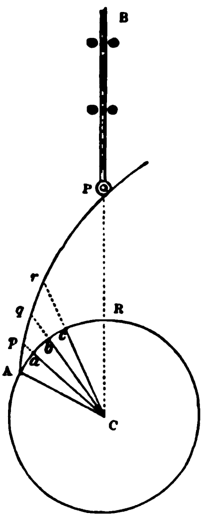


In this way a cam may be made to impart any required motion, and may reproduce in machinery those delicate and rapid movements which would otherwise demand the highest effort of skill from a practised workman.

19. The circular motion being uniform, the reciprocating piece may also move uniformly, or its velocity may be varied at pleasure.

I. Suppose that the reciprocating piece is a sliding bar, whose direction passes through the centre of motion of the cam plate; take C as this centre, let B P represent the sliding bar, and let A be the commencement of the curve of the cam plate. (Fig. 29.)

Fig. 29.



The curve A P may be set out as follows:—

With centre C and radius C A describe a circle, and let B P produced meet its circumference in R.

Divide A R into a number of equal arcs A a, a b, b c, &c.

Join C a, C b, C c, &c., and produce them to p, q, r, &c., making $a\,p$, $b\,q$, $c\,r$, &c. equal to the desired movements of B P in the corresponding positions of the cam plate: the curve A $p\ q\ r$...P will be the curve required.

This curve will often present in practice a very irregular shape, but in the particular case where the motion of P B is required to be uniform, it assumes a regular and well-known form.

Thus, let C A $= a$, C P $= r$, P C A $= \theta$, and let B P move in such a manner that P R $= m$ A R.

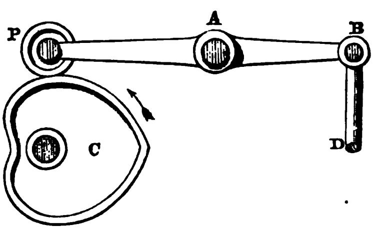
But P R $= r - a$, A R $= a\,\theta$, $\therefore\ r - a = m\,a\,\theta$, which is the equation to the spiral of Archimedes.

The heart wheel (Fig. 30) has been much used in machinery, and is formed by the union of two cams of the character just examined.

A curved plate, C, shaped like a heart, actuates a roller, P, which is placed at the end of a sliding bar, or which may

be attached to lever B A P, centred at some point A, and connected by a rod B D to the reciprocating piece. The peculiar form of the cam allows it to perform complete revolutions, and to cause an alternate ascent or descent of the roller P with a velocity which may be made quite uniform. A cam of this kind will only drive in one direction; the follower must therefore be brought back by the action of a weight or spring, and we further observe that its motion takes place in a plane perpendicular to the axis or shaft of the driver.

Fig. 30.



II. Let the direction of B P (Fig. 31) pass upon one side of C: draw C R $\perp^r$ to B P produced, describe a circle of

Fig. 31.

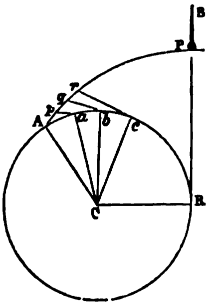
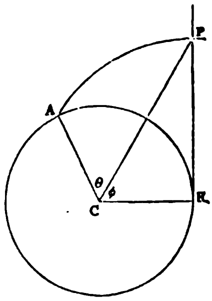


Fig. 32.



radius C R, and suppose the motion to begin when A coincides with R.

Divide A R into the equal intervals A *a*, *a b*, *b c*, &c., but now draw *a p*, *b q*, *c r*, &c., tangents to the circle, and equal

in length to the desired movements of B P during the corresponding periods of motion of the cam plate.

The curve A p q r ... P will be that required.

Its equation may be found as follows:—

Let C P $= r$, C A $= a$ (Fig. 32.)

A C P $= \theta$, P C R $= \phi$.

Suppose the linear velocity of A to be m times that of P, or that A R $= m$. R P,

$$\text{then } a(\theta + \phi) = m\, a \tan\phi$$

$$\text{But } \cos\phi = \frac{a}{r} \therefore \tan\phi = \sqrt{\frac{r^2}{a^2} - 1}$$

$$\therefore \theta + \cos^{-1}\frac{a}{r} = m\sqrt{\frac{r^2}{a^2} - 1}$$

Cor. Let $m = 1$, or A R = R P,

$$\therefore \theta + \cos^{-1}\frac{a}{r} = \sqrt{\frac{r^2}{a^2} - 1}$$

the equation to the involute of a circle.

It is evident that the curve A P would now be traced out by the end, P, of a string P R, which is being unwound from the circle.

20. Hitherto we have considered the cam to be a plane curve or groove; but there is no such restriction as to its form in practice. Let us examine the following very simple case, as well as the extension of which it admits.

Fig. 33.

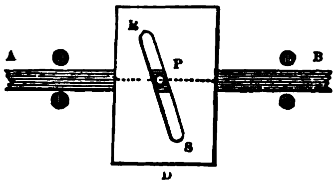
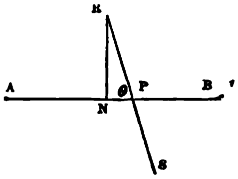


Fig. 34.



C D is a rectangle (Fig. 33) with a slit R S cut through it obliquely, a pin P fixed to the sliding bar A B works in

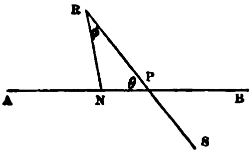
the slit. If the rectangle C D be moved in the direction R S, it will impart no motion to the bar A B; but if it be moved in any other direction, the pin P will be pushed to the right or left, and so a longitudinal movement will be communicated to the bar A B.

I. Suppose that C D is moved at right angles to A B; draw R N $\perp^r$ A B, and let A P R $= \theta$ (Fig. 34).

Then $$\frac{\text{velocity of C D}}{\text{velocity of A B}} = \frac{\text{R N}}{\text{P N}} = \tan\theta.$$

II. Let C D move in a direction inclined at an angle ϕ to R S. (Fig. 35.)

Fig. 35.

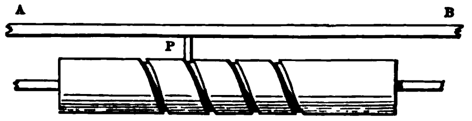


Draw R N in this direction,

then $$\frac{\text{velocity of C D}}{\text{velocity of A B}} = \frac{\text{R N}}{\text{N P}}$$
$$= \frac{\sin\theta}{\sin\phi}$$

Now let C D be wrapped round a cylinder; it will form a screw thread, and the revolution of the cylinder upon its axis will be equivalent to a motion of the rectangle at right angles to the bar, in the manner shown in the preceding article; we shall have, therefore, by the arrangement in the figure, a continuous uniform rectilinear motion of the bar A B during the revolution of the cylinder upon which the screw thread is traced. (Fig. 36.)

Fig. 36.



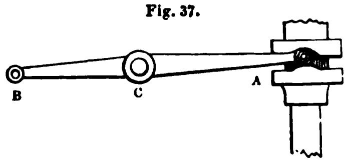
If the pitch of the screw be constant, the motion of P B will be uniform, and any change of velocity may be introduced by a proper variation in the direction of the screw thread.

If the screw be changed into a circular ring, A B will not move at all.

It is then a matter of indifference whether the cam be a groove traced upon a flat plate or a spiral helix running round a cylinder. In the first case motion ensues when the groove departs from the circular form, and the distance from the centre varies; in the second case motion ensues the moment the groove begins to deviate from the form of a ring, whose plane is perpendicular to the axis.

As an illustration of a cam of the latter character, we may refer to Fig. 37, which shows a form very much used where a small motion of a lever is required; the lever A C B is centred upon the point C, and will commence to move as soon as the pin at the end A reaches that portion of the ring which departs from the circular form.

Fig. 37.



This kind of cam has the property of giving a motion parallel to the axis upon which it is shaped.

21. We subjoin an example, devised some twenty years ago, in which a reciprocating movement is imparted to a frisket frame in printing machinery, and it will be presently seen that the required result can be obtained in a much more simple manner.

The use of a cam plate allows of an interval of rest at each end of the motion, and enables the printer to obtain an impression, and to place a fresh sheet of paper upon the form.

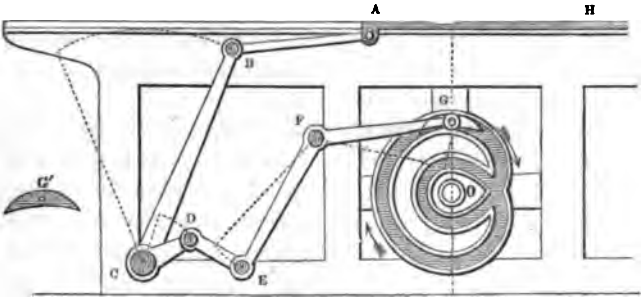
A H is the reciprocating frame attached to the combination of levers G F E D C B by the link A B. (Fig. 38.)

At the end of the lever, F G, is a sliding pin which travels along the grooves in the flat plate centred at O, and determines, by its position, the angular motion of the levers about the fixed centres at F and C.

Where the groove is circular, which occurs in those portions which are to the left hand of the vertical dotted line,

the levers remain at rest, and they change into the position shown by the dotted lines when the sliding pin passes from the outer to the inner channel. The pin is elongated in

Fig. 38.

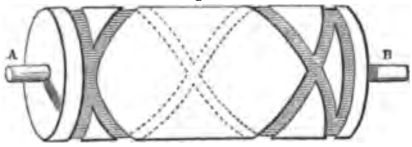


form, as shown at G′, and is thus capable of passing across the intersections of the groove.

Precisely the same character of movement may be obtained by the aid of a helical groove traced upon a revolving drum; the intervals of rest occur when the groove assumes the form of a flat ring, whose plane is perpendicular to the axis of the drum.

A right and left-handed screw thread is traced upon the worm barrel, A B, (Fig. 39), which revolves in one uniform direction; a pin attached to the table of a printing machine follows the path of the groove upon the barrel, and its form is elongated so as to enable it to pass in the right direction at the points where the grooves intersect.

Fig. 39.



The interval of rest commences with the entry of the pin into the flat ring at either end of the barrel, and may be made to occupy the whole or any part of a revolution of A B,

according as the grooves enter and leave the ring at the same or different points.

This construction dispenses with the complicated system of levers, which constitutes such a serious defect in the other arrangement.

Mr. Napier has patented an invention which causes the interval of 'rest' to endure beyond the period of one revolution of the barrel. (Fig. 40.)

At the entrance to the circular portion of the groove a moveable switch is placed, and it is provided that the switch shall be capable of twisting a little in either direction upon its point of support, and also that the pin upon which the switch rests shall admit of a small longitudinal movement parallel to the axis of the barrel, the pin itself being urged constantly to the right hand by the action of a spring.

Fig. 40.

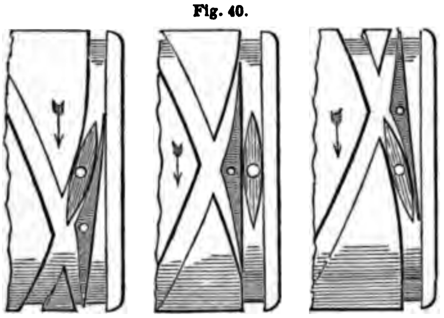


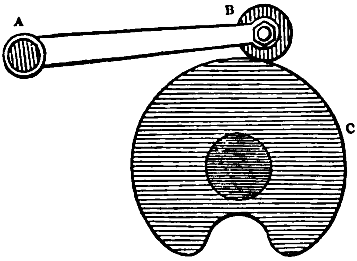
Fig. 1. Fig. 2. Fig. 3.

In Fig. 1 the shuttle is seen entering the circular portion of the groove, and twisting the switch into a position which will allow the shuttle to meet it again, as in Fig. 2, and to make a second journey round the circular ring.

The spring which presses the point of support of the switch to the right hand will now cause it to twist by means of the reaction which the passing pin affords, and the consequence will be that the switch will be left in the position shown in Fig. 3, and will guide the shuttle into the helical portion of the groove. Thus the period of rest will be that due to about one and two-thirds of a revolution of the barrel.

22. Cams are employed when it is required to effect a movement with extreme precision. Thus in the machine

Fig. 41.



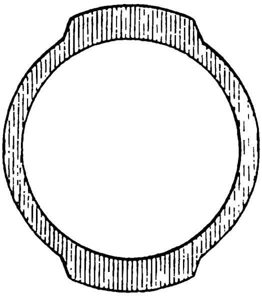
of Mr. Applegath for printing newspapers, the sheet of paper starts upon its journey to meet the type at a particular instant of time; an error of one-twelfth of a second would cause the impression to deviate nearly a foot from its correct position, and would throw two columns of letter-press off the sheet of paper. The accuracy with which the sheet is delivered is therefore very remarkable, and is insured by the assistance of the cam represented in Fig. 41.

As C revolves, the roller at B drops into the hollow of the plate, thereby determining the fall of the lever A B, and by it of another roller which starts the paper upon its course to the printing cylinder.

23. Cams are admirably adapted to the production of a short rapid motion, with intervals of rest.

In the expansive working of a steam-engine there are two positions of rest for the valve which regulates the admission of steam into the slide case, and it is desirable to move the valve as rapidly as possible from one position to the other.

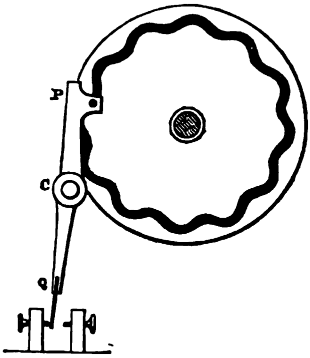
Fig. 42.



Hence the form of an *expansion cam*, as shown in Fig. 42.

24. Where the cam plate is required to effect more than one double oscillation of the sliding bar during each revolution, its edge must be formed into a corresponding number of waves.

Fig. 43.



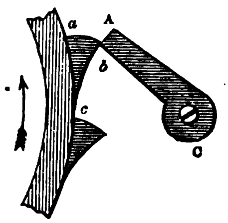
There is an example in telegraph commutators (Fig. 43), the interruptions of the current being caused by the vibrations of a lever, P C Q, centred at C, and whose angular position is determined by the pin at one end of it.

As the wheel revolves, it can impress any given number of double oscillations upon the lever.

25. In the striking part of a large clock the hammer may be raised by a cam, and may then be suffered to fall abruptly.

The figure represents the cam devised for the Westminster clock: the hammer rises and falls with the lever, A C (Fig. 44), and the cam is so formed that its action commences at the extremity of the lever, and never departs sensibly from the same point; the cam, *a b*, is a circle whose centre is at the point of intersection of the tangents to the rim of the wheel at the points *a* and *c*.

Fig. 44.

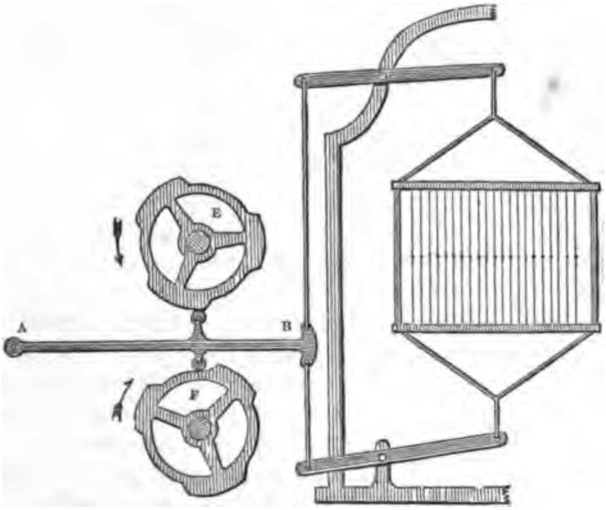


26. We remark, in conclusion, that when the mechanic causes the moving body to be influenced by a pin which exactly fits the groove along which it travels, it is obvious that the moving body will take the exact position determined by the pin; on the other hand, where the cam is merely a curved plate pushing a body before it, there is no certainty that this body will return unless it be

brought back by a weight or spring. Hence it arises that double cams have sometimes been employed in machinery, and we take the next example from an early form of power-loom.

A B is the treadle (Fig. 45), E and F are the cam wheels or tappets, which revolve in the directions shown by the

Fig. 45.



arrows, and in such relative positions that the projections and hollows are always exactly opposite to each other. As the cams rotate, the treadle, A B, is alternately elevated and depressed, and the threads of the warp are opened so as to permit the throw of the shuttle during the operation of weaving.

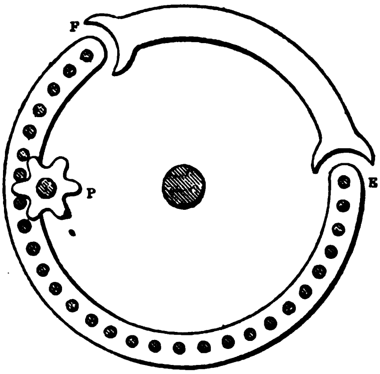
27. Mangle wheels form a separate class of contrivances for the conversion of circular into reciprocating motion.

A *mangle wheel* is usually a flat plate or disc furnished

with pins projecting from its face; these pins do not fill up an entire circle upon the wheel, but an interval is left, as shown at F, and E, Fig. 46.

A pinion, P, engages with the pins, and is supported in such a manner as to allow of its shifting from the inside to the outside, or conversely, by running round the pins at F and E.

Fig. 46.



The pinion, P, always turns in the same direction, and the direction of rotation of the mangle wheel is the same as that of P when the pinion is inside the circular arc, and in the opposite direction when the pinion passes to the outside.

By referring to the chapter upon the Teeth of Wheels, we may see that the inner and outer pitch circles coincide in the case of a pin wheel, and therefore that the rotation of the mangle wheel is precisely the same in both directions.

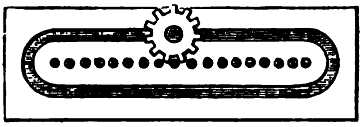
28. If the pins be replaced by a curved ring furnished with teeth, the mangle wheel will move more rapidly when the pinion is upon the inside circumference, and by giving certain arbitrary forms to this annulus, the velocities of advance and return may be modified at pleasure. Contrivances such as this belong to the early days of mechanical science.

Fig. 47.

29. The mangle wheel may be converted into a *mangle rack* by placing the pins or teeth in a straight line.

Here the pinion must be so suspended as to allow of its shifting from the upper to the under side of the rack.

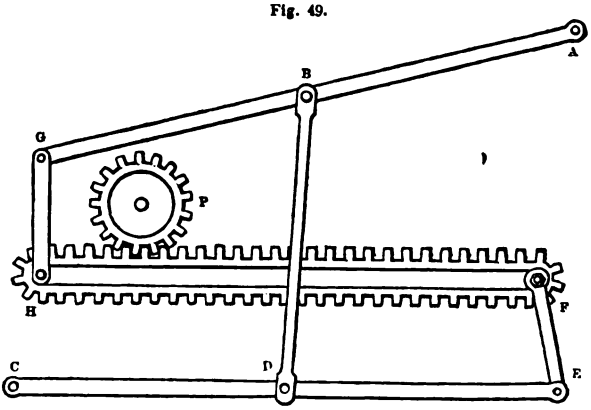
Fig. 48.



30. Sometimes the pinion is fixed, and the rack shifts laterally: an excellent form of this arrangement was introduced by Mr. Cowper, and serves to give a reciprocating movement to the table in his printing machine.

The rack, H F (Fig. 49) is attached to the system of bars in the manner exhibited in the diagram. A and C are centres of motion, and are the points where the bars are attached to the table. A G and C E are bisected in B and D, and are joined by the rod, B D; the rack, H F, is attached to the bars, A G and C E, by the connecting links, G H and F E.

Fig. 49.



The precise value of the contrivance will be understood upon referring to the section upon Parallel Motion, and it will be seen that when the pinion has pushed the rack to

either end of its path, the bars will move together, and will shift H F in a direction parallel to its length, and will thereby cause it to change from one side to the other of the pinion.

In this way the table, carrying the parallel bars and the rack, oscillates backwards and forwards, while the pinion, which transmits the force, remains fixed in space.

When this machine is applied to the printing of newspapers, the table moves at the rate of 70 inches in a second, and its weight, including the form of type, is about a ton and a half. When urged to its highest speed the machine will give 5,500 impressions in an hour, which is about the greatest number attainable under a construction of this kind; the true principle in rapid printing being that announced in the year 1790 by Mr. Nicholson, who proposed to place the type upon a cylinder having a continuous circular motion, and upon which another cylinder holding the paper should roll to obtain the impression. But although Mr. Nicholson enunciated the principle more than seventy years ago, and took out a patent for a mode of carrying it out, there is a wide difference between saying that a thing ought to be done, and showing the world how to do it in a practicable manner; hence it was not until late years that Mr. Applegath, and finally Mr. Hoe, were enabled so to arrange their cylinder printing machines upon the principle of continuous circular motion as to satisfy the wants of the 'Times' and the 'Daily Telegraph,' and to print some twelve or fourteen thousand sheets in an hour.

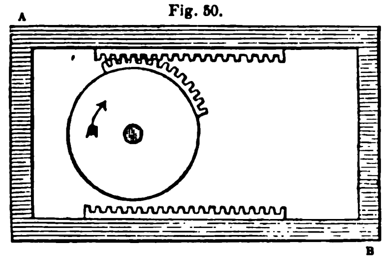
To recur to our shifting rack, it must be remarked that by reason of the great weight of the table, and the rapidity with which it moves, it would be quite unsafe to leave the rack and pinion in the present unassisted condition; a guide roller therefore determines the position of the pinion relatively to the rack, while the rack itself shifts laterally between guides.

But since, theoretically, the rods would cause H F to move always in a direction parallel to itself; so, practically,

they enforce the desired movement in the path of the guides with as little loss of power as possible.

31. If it be required that the reciprocation shall be intermittent, i. e. that there shall be intervals of rest, we may employ a segmental wheel and a double rack. (Fig. 50.)

Fig. 50.

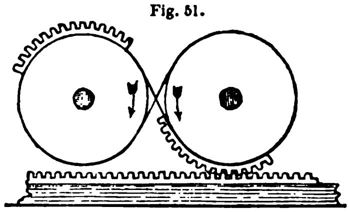


The teeth upon the pinion engage alternately with those upon either side of the sliding frame, A B, and the motion is of the character required. The intervals of rest are equal, and are separated by *equal* periods of time.

A pin upon the wheel and a guide upon the rack will ensure the due engagement of the teeth.

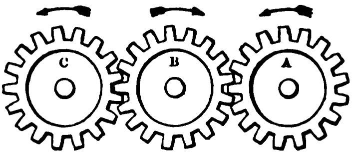
32. A mechanical equivalent to the above is found in the use of two segmental wheels and a single rack. (Fig. 51.) The segments must be equal, but they may be placed in different relative positions; and, as a consequence, the intervals of rest may be separated by *unequal* periods of time.

Fig. 51.



33. Combinations of toothed wheels, or something equivalent thereto, may be used in the conversion which we are

Fig. 52.

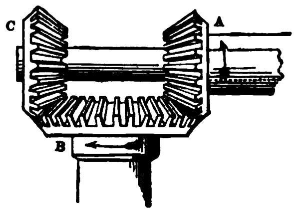


considering. *Let* A, B, C (Fig. 52) be three spur wheels in

gear, then A and B turn in opposite directions, but A and C turn in the same direction.

If, however, the wheels A and C be bevelled wheels, and be arranged with reference to B, as in the figure annexed, they will no longer turn in the same, but in opposite directions. (Fig. 53.)

Fig. 53.



There are many contrivances founded upon these simple propositions in the geometry of motion, of which we select the most prominent examples; premising at the same time one or two general observations.

34. In the transfer of force by machinery, the moving power is carried from one piece of shafting to another, throughout the whole length and breadth of the factory; it passes from point to point, enters each separate machine, and gives movement to all the parts which are prepared for its reception.

Now it must be remembered that the engine is never reversed, and that the power flows on in one uniform direction.

Take the case of a machine for planing iron: here the principal movement is that of a heavy table sliding forwards and backwards, and carrying the piece of metal which is the subject of the operation.

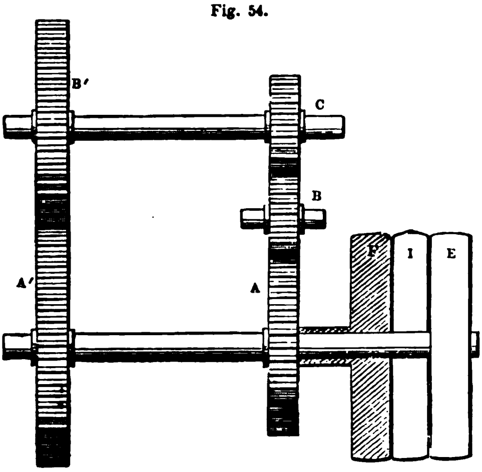
There are two methods of obtaining the desired result: the power may be poured, as it were, into the machine by a stream running always in one direction, and the reciprocation may be provided for by the construction of the internal parts, or the flow of the stream may be reversed by some intermediate arrangement external to the machine itself.

35. The former method is that usually adopted, and we shall first examine those machines where the reciprocation depends upon the internal construction of the moving parts.

The power is derived from the shafting by means of a band passing over a drum on the main shaft and over one of the three pulleys, E, I, F, at the entrance into the machine. (Fig. 54.)

In the annexed figure, which shows the principle of the movement adopted by Collier in his planing machines, and subsequently much used by other makers, the pulley E is keyed to a shaft terminating in the wheel A′; I is an idle pulley riding loose upon the same shaft; F is a pulley fixed to a pipe or hollow shaft, through which the shaft connecting E and A′ passes, and which terminates in the wheel A.

Fig. 54.



B′ C is a second shaft which carries the toothed wheels B′ and C.

B is an intermediate wheel riding upon a separate stud.

When the band drives the pulley E, we observe that A′ and B′ turn in opposite directions; whereas the motion is reversed when the band is shifted to F, for in that case A and C turn in the same direction. When the driving band is placed upon I, the machine remains at rest.

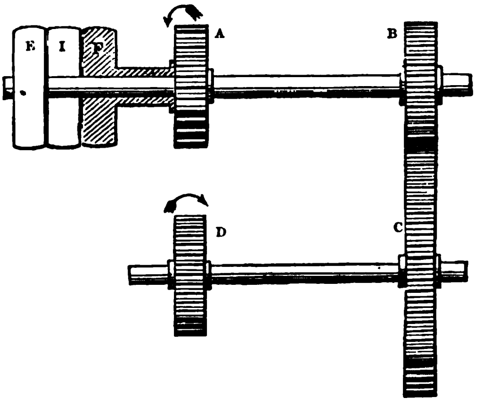
The rotation of B′C may be made much more rapid in one direction than in the other, and the construction is therefore very valuable in machinery for cutting metals.

The slow movement occurs while the cutting tool is removing a slip of metal, and the return brings the table rapidly back into the position suitable for a new cut.

36. This movement, slightly modified, is adopted in Collier's planing machine, and in those of other makers.

We give so much of the machine as will explain the method of reversing the motion of the table. (Fig. 55.) When the strap is upon the pulley F, the wheel A turns in one direction. When the strap is upon the pulley E, the motion passes to B, which turns with E, and thus the axis, C D, is made to revolve in the opposite direction with a reduced velocity. The wheels A and D both engage with

Fig. 55.



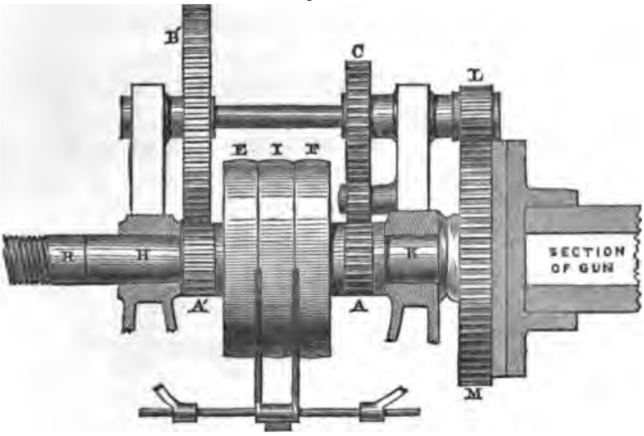
another wheel not shown in the drawing, which actuates the table, and the reversal takes place according as the moving power resides in A or in D.

37. There is an instance of the application of this contrivance in a machine arranged for the purpose of cutting

a screw-thread in the interior of the breech of an Armstrong gun.

Here F and E are working pulleys fastened respectively to the wheels A and A′ which ride loose upon the shaft H K; the wheel M is keyed to H K, and is further attached by a coupling to the muzzle of the gun operated upon.

Fig. 56.



When the strap is upon E, the motion travels from A′ to B′, and so on to L and M; whereas upon shifting the strap to F, the motion passes from A to C through a small intermediate wheel, and thence to L and M, and thus the gun is made to rotate alternately in opposite directions with unequal velocities.

The object of the machine is to copy upon the interior of the breech of the gun a screw thread which is formed upon a shaft R.

For this purpose the shaft H K is coupled to R, and moves with it, and a slide rest carrying a cutter advances longitudinally along the gun, with a motion derived directly from a nut which travels along the screw thread formed upon R.

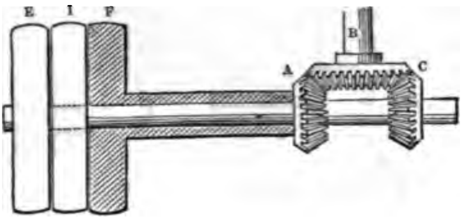
Since the cutter can only remove the metal while passing in one direction, there is a loss of time during the return motion which it is the object of this combination to reduce as much as possible.

38. A reversing motion with three pulleys and three bevil wheels is the following, and has been adopted by Mr. Whitworth in his planing machines:—

As before, there are three pulleys, E, I, and F, whereof I is an idle pulley, and rides loose upon the shaft; E is keyed to a shaft terminating in the bevil wheel C, and F sits upon a pipe through which the shaft connecting E and C passes, and which terminates in the bevil wheel A. (Fig. 57.)

B is a bevil wheel at the end of the shaft whose direction of rotation is to be reversed.

Fig. 57.



It is clear that the motion of the wheel B is reversed when the driving strap is shifted from E to F.

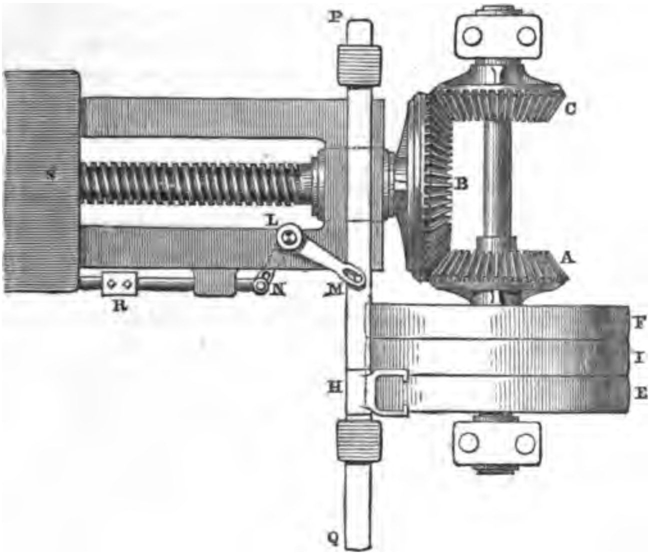
This is an example of the second case in Art. 33, and differs from that last considered in not permitting the motion of B to be more rapid in one direction than in the other.

It may, however, be so arranged as to produce this result by making A and C of unequal size, and causing them to gear respectively with two suitable wheels upon the axis of B.

39. The contrivance just described is shown in Fig. 58 as applied in a machine for rifling guns, and the method adopted is precisely that so generally employed in planing machines.

The three pulleys and the three bevil wheels are connected together in the manner already indicated, and the bevil wheel B by its rotation causes a saddle S carrying the rifling bar to move along the screw in the direction of its

Fig. 58.

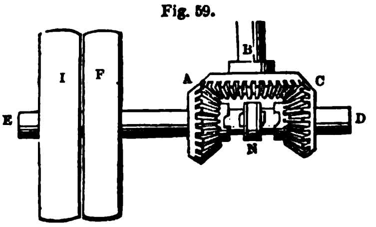


length. A bell crank lever, M L N, controls the bar P Q, which carries a fork used to shift the strap; the arms of the lever are in different horizontal planes, L N being the lower of the two; a moveable piece, R, fixed at any required point of the bar N R, which runs the whole length of the machine, is caught by a projection on the saddle as it passes to the right hand, and then the bell crank lever is actuated, and the fork is pushed from E to F. A weight falls over when this is taking place, and gives the motion with sharpness and decision, so as to prevent the strap from resting upon F during its passage. On the return of the saddle to the other end of its path, a similar projection again catches a second piece

upon the sliding bar N R, and the strap is thrown back from F to E.

40. The action of reversal by shifting the driving strap is comparatively slow, a more rapid movement is often wanted, as in screwing machines, and may be obtained by the use of a sliding clutch. We now employ one working pulley, and C is commonly the wheel whose rotation is to be reversed. (Fig. 59.)

Fig. 59.



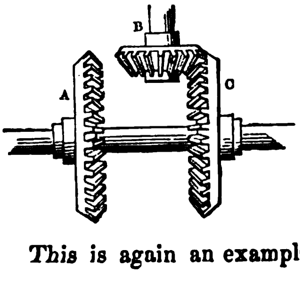
The wheels A and C ride loose upon the shaft E D, and the intention is to impart the motion of E D to A and C alternately.

For this purpose a sliding clutch N is fitted upon E D, and engages with A and C by turns; when N is moved up to A the rotation of the shaft is given to A, and carried on to C, whereby C rotates in the opposite direction to E D; but when N engages with C, of course that wheel rotates in the same direction as E D, and thus the reversal is obtained. The reversal of the wheel B, as well as that of C, occurs when N is shifted to the right or left.

41. In spinning machinery a reversing motion is frequently obtained as follows:—

A bevil wheel, B, is connected with the driving shaft, and the two bevil wheels, A and C, are keyed to the shaft whose motion is to be reversed; the interval between A and C being enlarged so that B can only be in gear with one of these wheels at the same time; the reversal is effected by shifting the piece A C longitudinally so as to allow B to engage with A and C alternately.

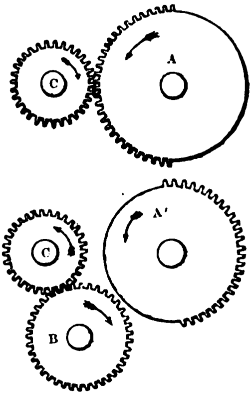
Fig. 60.



This is again an example of the second case in Art. 33.

42. Mr. Whitworth has proposed the subjoined arrangement for the reversal in a machine for cutting screws: we take it as an example of the use of segmental wheels, which, however, should always be avoided if possible. There is only one driving pulley, and two segmental wheels are keyed upon the driving shaft. They are close together in the machine, and for the sake of the explanation we have placed one above the other. The object is to effect the reversal of a shaft C: the segmental wheels A and A′ have teeth formed round one half of each circumference, and the toothed segments are in situations opposite to each other, as in Fig. 61.

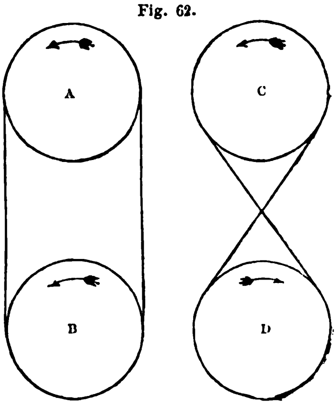
Fig. 61.



When the action of A ceases, that of A′ begins, and we have the wheels A and C, or the wheels A′, B, and C alternately in action, i. e. we have a reciprocation of C. This is a direct example of the first case in Art. 33.

43. Where the reciprocation is effected by a contrivance external to the machine itself, two driving bands may be employed: of these one is crossed, and the other is open, as shown in Fig. 62, and it is apparent that the lower discs B and D will turn in opposite directions, although they derive their motion from A and C, which, being driven directly by the engine, rotate always in the same direction.

Fig. 62.



44. The form which the arrangement assumes in practice is shown in Fig. 63, where one of the driving bands is represented as crossed, and the rotation of the shaft, H K, is derived from each band alternately.

Fig. 63.

There are four pulleys, whereof I and I′ are loose upon the shaft, and are twice as broad as B and D, which are working pulleys.

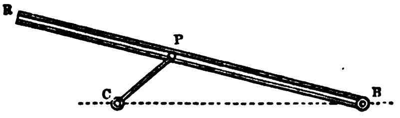
The bands are shifted by two forks, and remain always at the same distance from each other. In the figure the bands are both upon the idle pulleys, and H K remains at rest. When the bands are shifted to the right, the open strap drives B, and the crossed one remains upon I′: when the bands are shifted to the left, the crossed strap drives D, and the open one will be found upon the pulley I. Thus the shifting of the bands will effect the required reversal of the shaft H K.

The motion in either direction is the same, but it may be varied by placing drums of unequal size upon the upper shaft, and again by introducing an inequality between the pair I, B, and the pair I′, D. In order to make the explanation clearer, we have described the pulleys B and D as distinct from each other; it is usual, however, to replace them by a single pulley.

45. There is yet one most ancient contrivance for changing circular into reciprocating motion, which will repay the trouble of analysing it. In the form exhibited in the next

article it was used by the early Greek astronomers to represent mechanically the motion of the Moon.

Fig. 64.



Let the arm, C P, (Fig. 64) be centred at C, and convey motion to the grooved arm, B R, by means of a pin, P, which fits into the groove.

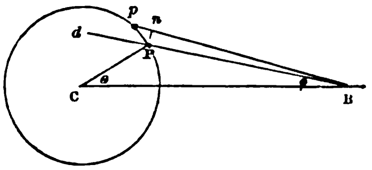
If C P be less than C B, the uniform circular motion of C P will cause a variable reciprocating motion in B R.

Let C (Fig. 65) be the centre of the circle described by P, P p a small arc, and P n a $\perp^r$ upon B p.

Let P C B $= \theta$, P B C $= \phi$, C P $= a$, C B $= c$.

Then $$\tan\phi = \frac{a \sin\theta}{c - a\cos\theta}$$

Fig. 65.



which gives the position of B P corresponding to that of the driving arm.

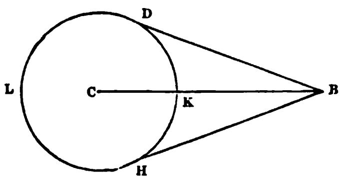
Again $$\frac{\angle^r \text{ vel. of B P}}{\angle^r \text{ vel. of C P}} = \frac{\text{P}n}{\text{P B}} \div \frac{\text{P}p}{\text{C P}} = \frac{\text{P}n}{\text{P B}} \times \frac{\text{C P}}{\text{P}p}$$

But $$\text{P}n = \text{P}p \cos p\text{P}n$$
$$= \text{P}p \cos d\text{P C}$$
$$= \text{P}p \cos(\theta + \phi)$$
$$\frac{\angle^r \text{ vel. of B P}}{\angle^r \text{ vel. of C P}} = \frac{\text{C P} \cos(\theta + \phi)}{\text{P B}}$$

If we draw B D, B H, tangents to the circle described by P, it will be evident that the times of oscillation of

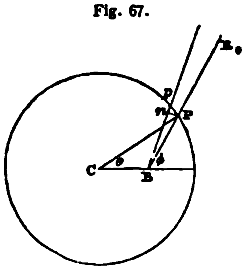
the arm will be unequal, and will be in the same proportion as the lengths of the arcs D L H, D K H. (Fig 66.)

Fig. 66.



46. If C P be greater than C B, there will be no reciprocation, but the uniform circular motion of C P will give rise

Fig. 67.



to a variable circular motion in B R, and thus *indirectly* we may effect a reciprocating movement with a quick return. (Fig. 67.)

As before, let C be the centre of the circle described by P.

$$\text{C P} = a, \ \text{C B} = c,$$

$$\text{P C B} = \theta, \ \text{P B D} = \phi,$$

$$\text{Then } \tan\phi = \frac{a \sin\theta}{a\cos\theta - c}$$

$$\text{And } \frac{\angle^{r}\text{ vel. of B P}}{\angle^{r}\text{ vel. of C P}} = \frac{\text{P}n}{\text{P B}} + \frac{\text{P}p}{\text{C P}}$$

$$= \frac{\text{P}p \cos \text{C}p\text{B}}{\text{P B}} \times \frac{\text{C P}}{\text{P}p}$$

$$= \frac{\text{C P} \cos \text{C P B}}{\text{P B}}$$

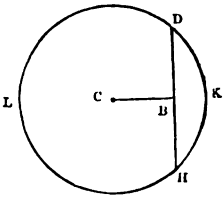
[redacted]

If C B be small, the angle C P B will be small also, whence $\cos$ C P B $= 1$ nearly, and the $\angle^r$ vel. of B P $\propto \frac{1}{\text{B P}}$ nearly.

The angular vel. of B P will be equal to that of C P when C P . $\cos$ C P B $=$ B P, or when C B P is a right angle.

In the circle described by P draw D H $\perp^r$ C B, then the times of a half revolution of B P will be in the proportion of the arcs D K H and D L H. (Fig. 68.)

Fig. 68.



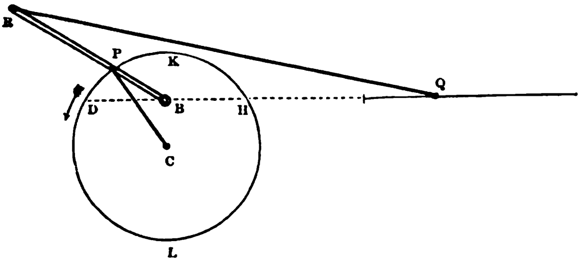
If B P be made to carry a link, R Q, as in the case of the crank and connecting rod, the linear motion of Q will be the same in amount as if B R revolved uniformly, but the periods of each reciprocation will in general be different. (Fig. 69.)

The difference in the times of oscillation will depend upon the direction of the line in which Q moves.

The best position for that line is in a direction $\perp^r$ to C B: a little consideration will show that the times of oscillation are always as the arcs D K H and D L H, and that the inequality between these arcs is greatest when D H is $\perp^r$ to C B, and diminishes to zero when D H passes through C B.

47. We have now an arrangement very suitable for effecting a quick return of the cutter in a shaping machine. (Fig. 69.)

Fig. 69.



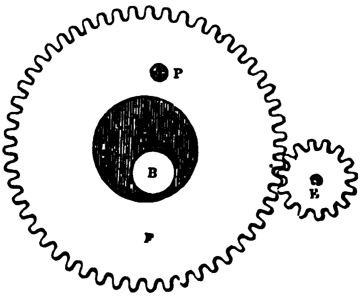
Let one end of a connecting rod be made to oscillate in

a line $\perp^{r}$ C B, or nearly so, and let the crank B R be driven by an arm, C P, which revolves uniformly in the direction of the arrow, we at once perceive that Q will advance slowly and return quickly, the periods of advance and return being as the arcs D L H and D K H.

48. Such a direct construction is not very convenient for the transmission of force, and it has been so modified by Mr. Whitworth in his Shaping Machine, that the principle remains unchanged, while the details of the moving parts have undergone some transformation.

This machine is analogous to a planing machine, but there is no moveable table; the piece of metal to be shaped is fixed and the cutter travels over it. The object of the contrivance is to economise time, and to bring the cutter rapidly back after it has done its work.

Fig. 70.



The arm C P (Fig. 70) is obtained *indirectly* by fixing a pin, P, upon the face of a plate, F, which rides loose upon a shaft, C, and is driven by a pinion, E.

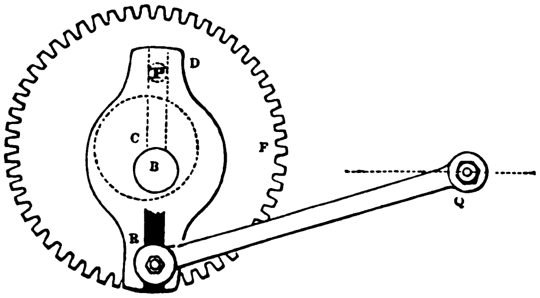
As the wheel F revolves upon the shaft represented by the shaded circle, the pin moves round it, and remains at a constant distance from its centre.

A hole, B, is bored in the shaft, C, and serves as a centre of motion for a crank piece, D R, shown in Fig. 71. The connecting rod, R Q, is attached to one side of this crank piece, and the pin, P, works in a groove upon the other side. Thus the rotation of the crank causes the end Q to oscillate backwards and forwards, and to return more rapidly than it advances.

The length of the stroke made by Q must be regulated

by the character of the work done, and is made greater or less by shifting R farther from or nearer to B; this adjust-

Fig. 71.

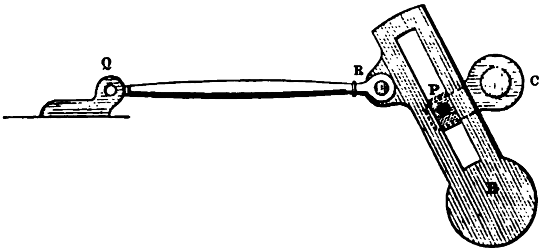


ment does not affect the inequality in the periods of advance and return which the machine is intended to produce.

49. There have been some shaping machines constructed also upon the principle discussed in Art. **45.**

Here the crank, B R, which actuates the cutter by means of the connecting rod, R Q, is made to vibrate slowly in

Fig. 72.



one direction and rapidly in the other by deriving its motion from the arm C P which revolves uniformly, according to the method explained. (Fig. 72.)

The movement just examined is useful also in looms for weaving carpets; the wires upon which the looped fabric is formed may be inserted rapidly between the warp

threads, but they should be withdrawn more slowly after the weft has been beaten up. Accordingly this slotted lever has been employed precisely in the same way as in the shaping machine described in the last paragraph, in order to actuate a moving piece which inserts and withdraws the wires.

50. From the invention of the Art of Printing in the year 1450 till the year 1798 no material improvement was made in the Printing Press. The earliest representation of a press occurs as a device in books printed by Ascensius; there is scarcely any difference between it and a modern press, and it is truly a matter of astonishment that so long a period as nearly 350 years should have rolled on without some improvement being made in so important a machine.

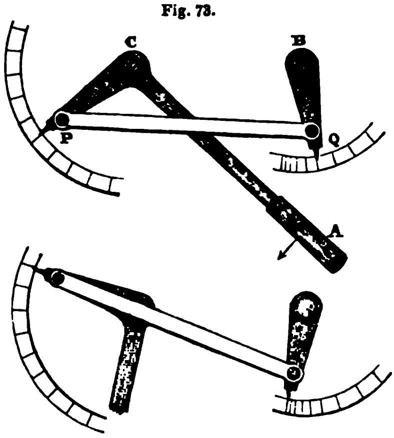
The wooden press consists of two upright pieces of timber joined by transverse pieces at the top and near the bottom; a screw furnished with a lever works into the top piece, and by its descent forces down a block of mahogany, called the 'platten,' and thus presses the sheet of paper upon the type, which is laid upon a smooth slab of stone embedded in a box underneath. In the year 1798 Lord Stanhope constructed the press of iron instead of wood, and at once transferred the machine from the hands of the carpenter to those of the engineer; he further added a beautiful combination of levers for giving motion to the screw, causing thereby the platten to descend with decreasing rapidity, and consequently increasing force, until it reached the type, when a very great power was obtained.

The Stanhope levers may be regarded as a simple modification of the crank and connecting rod, and may be arrived at as follows.

Suppose that C P and P Q (Fig. 73) represent the crank and connecting rod discussed in the early part of the chapter, and let Q be made to oscillate in a circular arc by fixing it to the end of a lever B Q, which is moveable about a centre at B.

If a force, F, be applied at the end of the handle, A C, so as to turn the crank, C P, uniformly in the direction indicated, the arm, B Q, will, under proper conditions, move with a continually decreasing velocity until it comes to rest, and then any further motion of C P will cause it to return.

Fig. 73.



The lower diagram shows the levers in this extreme position, and the graduated scales at P and Q indicate the relative angular movements of C P and B Q.

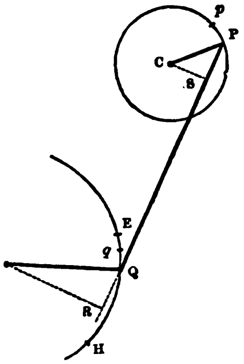
Now the motion, interpreted as a question in mechanics, implies that the resistance at Q necessary to balance the force which turns the crank is increasing rapidly as the rotation of B Q decreases, and that there is no limit theoretically to the pressure which will be felt as a pull at Q by reason of the force F. In practice this extreme pressure is exerted through so very small a space that the theoretical advantages are scarcely realised, but the arrangement is exceedingly useful as applied in the Printing Press.

The lever B Q is there employed to turn the screw that acts upon the platten; the workman gives a pull to the handle, A C, and by doing so causes the platten to descend with a motion which is at first considerable, and afterwards rapidly dies away. At the same time, the limited amount of power which is exerted comes out with greatly magnified effect in impressing the paper upon the type.

51. There is no difficulty in arranging that the onward motion of C P shall cause B Q to reciprocate, but if it

be required that CP shall make complete revolutions, some consideration will be necessary. In Fig. 74 the points E and H, where the oscillation of Q terminates, are given by the condition that CP and PQ fall into the same straight line.

Fig. 74.



$$\therefore \; CE = PQ - CP$$
$$CH = PQ + CP$$

If CP is to make complete revolutions, it will be further necessary that CP and PQ shall come into a straight line before BQ and PQ have the power to do so: hence the required conditions are that

$$CB + BQ > CH \text{ or } > PQ + CP$$

And $$CB - BQ < CE \text{ or } < PQ - CP$$

52. The remaining matter to be noticed in connection with the motion of CP and BQ is a comparison of their angular velocities.

Draw CS, BR perpendiculars upon the direction of PQ, and let P and Q move to p and q during the smallest conceivable interval at the beginning of the motion. (Fig. 74.) Then the resolved part of the motion of Q in direction $QP = Qq \cos PQq = Qq \sin BQR$

$$= Qq \times \frac{BR}{BQ} = BR \times \frac{Qq}{BQ} = BR \times \text{angle } QBq.$$

So also the resolved part of the motion of P in direction $QP = CS \times \text{angle } PCp$.

But in the first instant of motion these resolved parts are equal to each other. $\therefore BR \times \text{angle } QBq = CS \times \text{angle } PCp$

$$\therefore \frac{\text{angle } QBq}{\text{angle } PCp} = \frac{CS}{BR} \text{ or } \frac{\angle^r \text{ vel. of } BQ}{\angle^r \text{ vel. of } CP} = \frac{CS}{BR}$$

We shall hereafter comprehend the value of this proposition, with which we conclude the present chapter.

CHAPTER II.

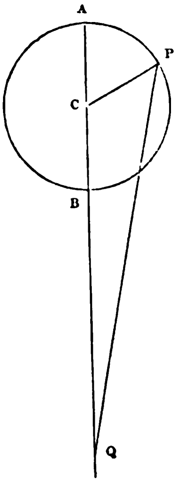
ON THE CONVERSION OF RECIPROCATING INTO CIRCULAR MOTION.

53. It has been shown that the motion of a point in a circle results from the combination of two reciprocating movements in lines at right angles to one another, and that circular may be converted into reciprocating motion by the suppression of one of these movements.

The reconversion of reciprocating into circular motion is not a problem of the same kind, as we now require the creation of a movement, instead of its suppression: such a creation is impossible in a strict mathematical sense, but is practically attainable by mechanical construction.

54. We recur now to the contrivance of the crank and connecting rod as one of the most obvious methods of solving the problem; it is clear that the travel of Q in a line pointing to C will cause the rotation of C P, and compel P to move in a circular arc. (Fig. 75.)

Fig. 75.



But unless C P possesses inertia, or is attached to some heavy body as a fly-wheel, which, when once set in motion, cannot suddenly come to rest, there will be two points where the power exerted at Q will fail to continue the motion, and these points are evidently at A and B, where C P Q straightens into a right line.

It is usual to call A and B the 'dead points' in the motion, and P must be made to pass through them without deriving any aid from Q.

In applying the crank and connecting rod to beam-engines, the piston rod is attached by Watts's parallel motion to one end of a heavy iron beam, and the rotation of the fly-wheel is derived by the aid of a connecting rod or spear uniting the other end of the beam with a crank which turns the fly wheel. The application to direct acting engines, of which the locomotive engine may be taken as the type, has been already noticed, and the student will now understand that the mechanical working would be incomplete unless the crank were attached to a fly-wheel or other heavy revolving body balanced upon its centre, which would carry P through those portions of its path near to the dead points, and would also act as a reservoir, into which the force of the steam might be poured, as it were, unequally, and from which it might be drawn off uniformly, so as to cause the engine to work smoothly and evenly.

In marine engines, where the fly-wheel is not admissible, and where the engine must admit of being readily started in any position, two separate and independent pistons give motion to the crank shaft. In this case the two cranks are placed at right angles to each other, so that when one crank is in a bad position, the other is in a good one.

The same plan holds in the construction of locomotive engines.

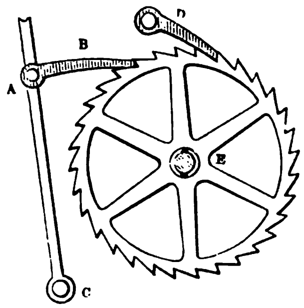
55. In the instances considered, the circular motion derived from the reciprocating piece is *continuous*; it now remains for us to examine a class of contrivances for producing the like result where the circular motion is *intermittent*.

The circular motion being that of a wheel turning upon its axis, it may be arranged that one-half of the reciprocating movement shall be suppressed, and that the other half shall always push the wheel in the same direction; this is the

principle of the *ratchet wheel*: or the reciprocating piece may be of the form shown in escapements which produce a recoil, and its pallets will then act upon opposite sides of the wheel, and push it always in one uniform direction.

56. A wheel provided with pins or teeth of a suitable form, and which receives an intermittent circular motion from some vibrating piece, is called a *ratchet wheel.* (Fig. 76.)

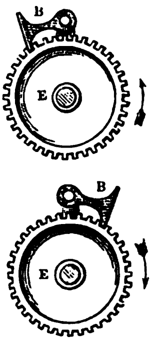
Fig. 76.



Here E represents the ratchet wheel furnished with teeth shaped like those of a saw, and A B, the driver, is a click or paul, jointed at one end, A, to a moveable arm, A C, which has a vibrating motion upon C as a centre.

As A C moves to the right hand, the click, B, pushes the wheel before it through a certain space; upon the return of A C, the click, B, slides over the points of the teeth, and is ready again to push the wheel through the same space as before, being in all cases pressed against the teeth by its weight or by a spring. A detent, D, prevents the wheel from receding, while B is moving over the teeth.

Fig. 77.



In this way the reciprocating movement of A B is rendered inoperative in one direction, and the circular motion results from the suppression of one half of the reciprocating movement. The wheel, E, and the vibrating arm, A C, are often centred upon the same axis.

The usual form of the teeth is that given in the figure, and the result is that the wheel can only be driven in one direction; but in machinery for cutting metals it is frequently desirable

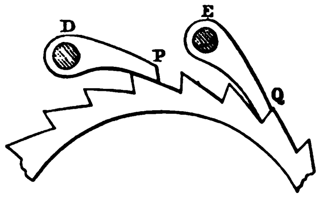
to drive the wheel indifferently in either direction; in that case Mr. Whitworth adopts the annexed construction. (Fig. 77.) The ratchet wheel has radial teeth, and the click, B, can take the two positions shown in the figure, and can drive the wheel in opposite directions.

57. Everyone must have seen the application of the ratchet wheel to capstans and windlasses, where it is introduced in order to prevent the recoil of the barrel; the same purpose for which it is applied in clocks and watches.

It was a very early improvement to provide two pauls of different lengths, termed by the sailors 'paul and half paul,' and thereby to hold up the barrel at shorter intervals during the winding on of the rope; in fact, a ratchet wheel of eight teeth thus became practically equivalent to one of sixteen teeth, and the men were better protected from any injury which might be caused by the sudden recoil of their handspikes.

The principle of this contrivance is very intelligible, and is shown in Fig. 78, where the two pauls, D P, E Q, differ in length by half the space of a tooth.

Fig. 78.



As the wheel advances by intervals of half a tooth, each paul falls alternately, and the same effect is produced as if the number of teeth were doubled, and there was only one paul.

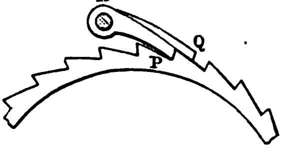
In the same way three pauls might be used, each differing in length by one-third of the space of a tooth, and so the subdivision might be extended.

58. Where the pauls or clicks act as drivers instead of detents, the same holds good. Conceive now that two clicks, D P, D Q (Fig. 79), differing in length by half the space of a tooth, are hung upon a pin D at the end of the arm which drives the ratchet wheel; they will manifestly

engage the wheel alternately, and will move it as if there were twice as many teeth driven by one click.

And so for three or a greater number of clicks.

Fig. 79.



In practice it is often required to move a ratchet wheel through certain exact spaces, differing by small intervals; where such is the case it is better not to attempt a minute subdivision of the teeth, as they become liable to break and wear away and the action is uncertain, but recourse may be had to this method of placing three or four clicks upon the driving arm.

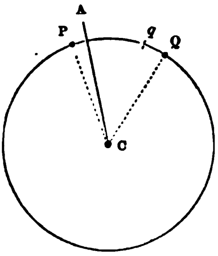
On referring back to Fig. 16, the student will find an example of the use of a ratchet wheel. A link, H K, connects the reciprocating frame, F G, with an arm, L M, carrying a click at Q; thus the oscillations of the frame are received by the arm, and the wheel is advanced a certain number of teeth upon each motion to the right. The number of teeth taken up can be regulated by adjusting the distance of K from L by means of a screw; the nearer K is brought to L, the greater will be the advance of the ratchet wheel at each stroke.

The object of the arrangement is to feed on the rod of lead from which the material for each bullet is cut, and by placing three clicks at Q instead of one, the amount to be advanced for bullets of different sizes may be regulated with considerable nicety.

59. The method here adopted for regulating the integral number of teeth taken up is one in very common use. There is, however, another principle upon which a like result can be obtained, which has been introduced by Mr. Whitworth in his Planing Machine. Let C A represent a rod centred at C, upon which point also there is centred a circle carrying two pins at P and Q.

Suppose now that the circle vibrates regularly to the right and left through a definite angle, P C Q, then it will be seen that if P and Q embrace the rod closely upon opposite sides, the whole vibration of the circle will be imparted to C A.

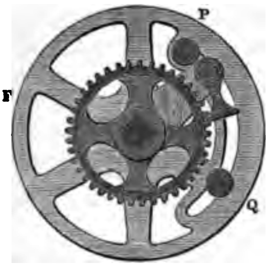
Fig. 80.



If, however, Q be moved to *q*, the arm C A will be pushed to Q by the pin P when moving to the right, but will only return as far as Q can carry it, i.e. to *q*, and the vibration will take place through an angle Q C *q* instead of an angle Q C P, and in this way, by separating P and Q, the motion of A C may be reduced till it ceases altogether.

A ratchet wheel, an arm carrying a click, and another wheel provided with a circular slot, are placed in the order stated upon the same axis, and can all move independently of each other. There are two moveable pins in the circular slot, which are capable of being fixed in any position by nuts at the back of the wheel, and which embrace the arm carrying the click, but do not reach the click itself.

Fig. 81.

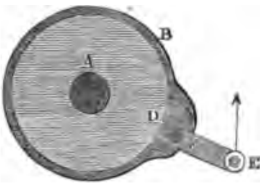


The ratchet wheel is connected with a screw which advances the cutter across the table, and the object is to impart definite but varying amounts of rotation to the screw after each cut has been taken.

The wheel F receives a fixed amount of vibration from the table, and will impart the whole thereof to the click if P and Q be made to embrace the arm closely upon each side; or it will impart any less amount, gradually diminishing to zero, as P and Q are separated to greater intervals along the groove, and thus the feed of the cutter may be *regulated* according to the demands of the work.

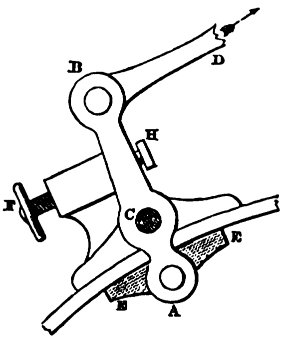
60. A mechanical equivalent for the teeth and click may be found in what is termed *a nipping lever*, constructed upon the following principle. Conceive that a loose ring, B, surrounds a disc, A, and that upon a projecting part of the ring there is a short lever, D E, centred. This lever is moveable about a fulcrum at F, near to the wheel, and terminates at one end in a concave cheek, D, fitting the rim of the disc. On applying a force at E the lever will nip or bite upon the disc, and the friction set up may be enough to cause them to move together as if they were one piece. Upon reversing the pressure at E, the nipping lever will be released and the ring will slide a short space upon the disc: thus the action of a ratchet wheel is imitated.

Fig. 82.



61. The ratchet wheel has been much used in obtaining an advance of the piece of timber at each stroke of the saw in sawing machines. A substitute has been found in an adaptation of this nipping lever, and is commonly known as the *silent feed.*

Fig. 83.



An arm A B (Fig. 79), centred at C, rides upon a saddle which rests upon the outer rim of a wheel; a piece, E E, is attached to one end of the arm and admits of being pressed firmly against the inside of the rim of the wheel which carries the saddle.

It is clear that when the end, B, of the arm, A C B, is pulled to the right hand, the rim of the wheel will be grasped or nipped firmly between the saddle and the piece, E E, and that the pull in B D will move the saddle and wheel together, as if they were made in one piece. When B is pushed back,

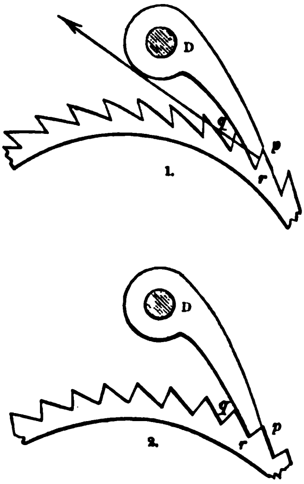
a stop prevents B C A from turning more than is sufficient to loosen the hold of E E, and the saddle slides upon the rim through a small space.

In this manner the action of a ratchet wheel is imitated, and, by properly regulating the amount of motion communicated by the link B D, we obtain an equivalent for a ratchet wheel with an indefinite number of teeth.

A screw, F, may be employed to bring up a stop, H, towards the arm, A C B, and thus to prevent the arm from twisting into the position which gives rise to the grip of E E. The saddle will then slide in both directions without imparting any motion to the wheel, a result which is obtained in an ordinary ratchet wheel by throwing the click off the teeth.

62. As regards the action between the teeth and the detent, we observe that the wheel must tend to hold the detent down by the pressure which it exerts, and that it will do so as long as the line of pressure on the surface, $p\ r$, falls below the centre of motion D. (Fig. 84.) If the angle $q\ r\ p$ were opened out much more, as shown in Fig. 2, the $\perp^r$ upon $p\ r$ might rise above D, and the detent would then fail to hold the wheel.

Fig. 84.



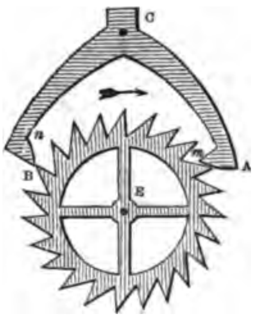
Further, the click has to return by slipping over the points of the teeth; the condition for this result is that the $\perp^r$ to the surface $q\ r$ shall fall between D and the centre of the wheel.

Where very little force is required to hold the wheel, and

the exact position is of consequence, as in counting machinery, the teeth may be pins, and the detent may be a roller pressed against them by a spring.

63. Where the ratchet wheel moves at each vibration of the driver, and not during every alternate movement, an escapement, or something approximating thereto, must be employed. The action now takes place alternately upon opposite sides of the wheel. (Fig. 85.)

Fig. 85.



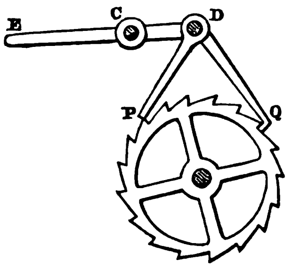
When A *m*, in the common recoil escapement, moves to the left, it presses down the point of a tooth; when B *n* moves to the right, it presses up the point of another tooth, and each action advances the wheel in the same direction.

It will be observed that this direction is the opposite to that in which the wheel revolves when driving the escapement.

64. The same action results were two clicks are hung upon a vibrating bar, and one of them terminates in a hook.

The bar, E C D (Fig. 86), vibrates on C as a centre, and the pieces Q D, P D, hang at the extremity D. When P pushes on the wheel, D Q slips over a tooth; and when Q is driving, the click P also passes over a tooth; and thus the wheel advances upon each vibration of the moving arm. This contrivance is due to Lagarousse.

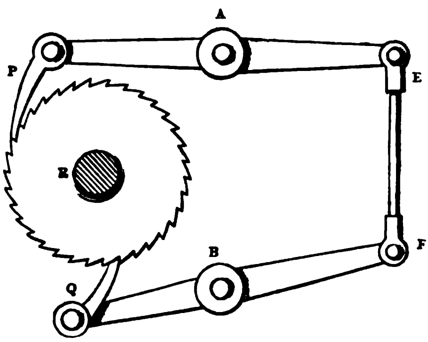
Fig. 86.



The hook may be replaced by a click, turned in the reverse direction, as in the annexed example, which is taken from

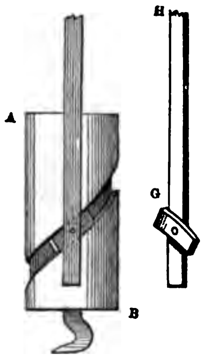
the specification of a patent planing machine, where it was intended that the cutter should act during each movement of the table. Here the levers which carry the clicks are moveable about centres at A and B, and are connected by a link, E F. (Fig. 87.)

Fig. 87.



65. The converse of the contrivance described in Art. 20 may also be used to convert reciprocating into circular motion; that is to say, the bar may be employed to turn the screw barrel, instead of the screw driving the bar; but such an arrangement gives rise to a great increase of friction, and is only met with when a small amount of force is to be exerted. There is an instance in a light drill, where the rotation is derived by pushing a nut up and down a rod, upon which a screw of rapid pitch is formed, the drill rotating in opposite directions as the nut rises and falls.

Fig. 88.



The movement was at one time proposed by Mr. Whitworth in order to obtain a reversing motion of the cutter in planing machinery. A rod, H G, (Fig. 88) was provided with a sort of tooth, G, which fitted exactly into a groove in the form of a screw thread traced upon the cylinder A B. As the rod moved up and down it reversed the position of the cutter, and enabled it to act while the table was moving in either direction.

CHAPTER III.

ON THE TEETH OF WHEELS.

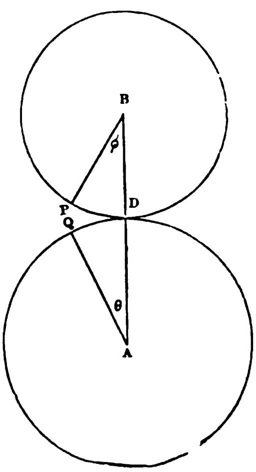
66. We propose now to enter into a mathematical investigation of the forms of teeth adapted for the transmission of motion or force in combinations of wheel-work, and we have already stated the general nature of the problem.

It is required to shape the teeth or projections upon the edges of two circular discs in such a manner that the motion resulting from the mutual action of the teeth upon the discs shall be precisely the same as the rolling action of those definite circles known as the pitch circles of the discs in question.

The various geometrical propositions which enable us to accomplish the solution of the problem will be given in detail, and the practical application of these theorems will also be indicated as briefly as possible.

67. When two circles roll together, their angular velocities are inversely as the radii of the circles.

Fig. 89.



Let the circles centred at A and B move by rolling through the corresponding angles PBD and QAD. (Fig. 89.)

Let $\text{AD} = a$, $\text{BD} = b$,

$\text{QAD} = \theta$, $\text{PBD} = \phi$,

Then $\text{QD} = a\,\theta$, $\text{PD} = b\,\phi$,

But $\text{QD} = \text{PD}$ $\therefore a\,\theta = b\,\phi$

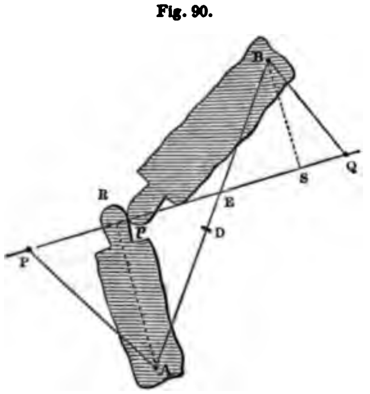
$$\therefore \frac{\theta}{\phi} = \frac{b}{a}$$

$$\text{or} \quad \frac{\angle^{\text{r}} \text{ vel. of A}}{\angle^{\text{r}} \text{ vel. of B}} = \frac{b}{a}$$

which proves the proposition.

68. Let A and B (Fig. 90) be the centres of motion of two pieces provided with teeth of some determinate form, and conceive that p is the point of contact of the teeth in question: draw P p Q, a common $\perp^r$ to the touching curves cutting A B in E. Let P and Q be the centres of the circles of curvature of the curves which touch at p, and draw A R, B S, $\perp^r$ to B Q. Then, in the first instant of motion, P Q may be regarded as constant, and the angular velocities of the two pieces will be identical with those of A P and B Q.

Fig. 90.



But by Art. (52) $\dfrac{\angle^r \text{ vel. of A P}}{\angle^r \text{ vel. of B Q}} = \dfrac{\text{B S}}{\text{A R}} = \dfrac{\text{B E}}{\text{A E}}$

whence $\dfrac{\angle^r \text{ vel. of piece A}}{\angle^r \text{ vel. of piece B}} = \dfrac{\text{B E}}{\text{A E}}$

Suppose it to be required that the angular velocities of the two pieces shall be the same as those of the pitch circles of radii A D, B D. We must now form the curves so that E shall coincide with D, and shall never leave it during the motion; in other words, the common perpendicular to the surfaces of any two teeth in contact must always pass through the point of contact of the two pitch circles.

If the teeth can be formed so as to satisfy this condition, the problem will be fully solved, and we proceed to give the solutions which have been devised by the ingenuity of mathematicians.

69. Def. An epicycloid is a curve traced out by a point, P, in the circumference of one circle, which rolls upon the

convex arc of another circle. This curve is represented by the dotted line in Figure 91.

Fig. 91.

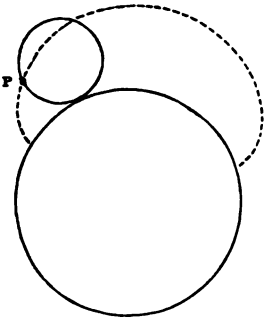
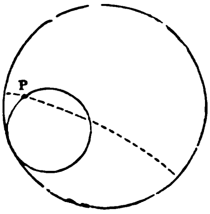


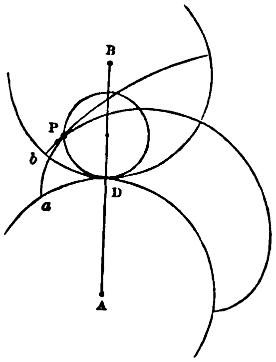
Fig. 92.



Def. A hypocycloid is a curve traced out by a point, P, in the circumference of one circle, which rolls upon the concave arc of another circle. This curve is represented by the dotted line in Figure 92.

70. Let now the *same circle* roll upon the outside of the circle A and the inside of the circle B; bring the circles together till the two curves and the circles also touch, as in Fig. 93, and it will be found that the common perpendicular at the point of contact of the curves passes through D.

Fig. 93.



The truth of this statement is evident from the consideration that when the curves touch, the describing circle may be taken as being ready to generate either the one curve or the other; now the describing circle cannot do this unless it be resting on both circumferences indifferently, i. e. unless b D = a D, and the common perpendicular to the curves at P passes through the point D.

71. We have now obtained two curves which satisfy the geometrical requirements of the problem, and it remains to put our theory into practice.

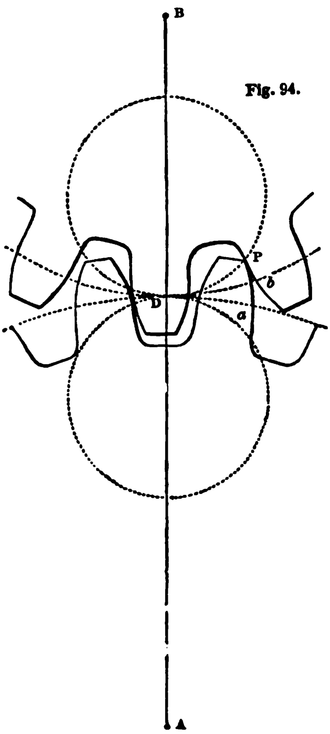


Fig. 94.

The epicycloid and hypocycloid which form the acting surfaces of two teeth must be produced by one and the same describing circle.

Let A and B be the two pitch circles. (Fig. 94.) Take a circle of any convenient size less than either A or B, and call it G: with G describe an epicycloid upon A and a hypocycloid upon B; let these curves determine the acting surfaces *a* P, *b* P, of two teeth in contact at P; then the tooth *a* P will press against *b* P so that the perpendicular to the surfaces in contact at P shall pass through D, and the relative angular velocities of two pieces centred at A and B, and furnished with these teeth, will be the same as those of the two pitch circles.

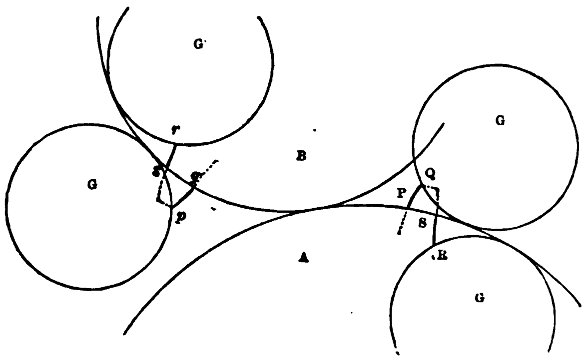
As far as we have gone we have described the point of a tooth upon A and the flank of one upon B, and have supposed A to drive B. If the conditions were reversed, and B were to drive A, we should again have to obtain from one describing circle the curves suitable for the point of a tooth upon B and the flank of one upon A. This describing circle *is not necessarily* of the same size as the former one, but it

is very advantageous to make it so, and we shall therefore assume that the teeth upon A and B are formed by the *same* describing circle.

72. To complete the form of the teeth so that either A or B may drive, the construction is the following:

Let the describing circle G (Fig. 95) trace P Q, S R upon A, and *p q*, *s r* upon B. Then P Q determines the form of

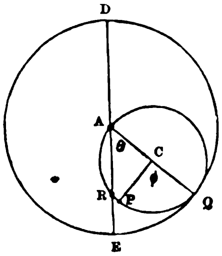
Fig. 95.



all the points of the teeth upon A, and S R that of the flanks, and in the same way *p q* and *s r* together make the point and flank of a tooth upon B.

73. There are two particular cases of the above solution yet to be examined.

Fig. 96.



When the diameter of the circle which describes a hypocycloid is taken equal to the radius of the circle within which it rolls, the curve becomes a straight line.

Let C (Fig. 96) be the centre of the describing circle at any time, and P the corresponding position of the describing point.

Suppose that P begins to move from E, so that the arc P Q may be equal to the arc E Q.

Join C P, A E; let A E Q $= \theta$, P C Q $= \phi$

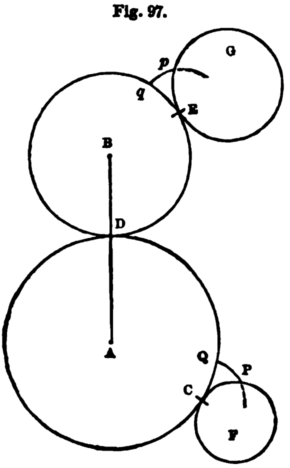
$$\text{Then } PQ = EQ$$
$$\text{or } CQ \times \phi = AE \times \theta$$
$$\text{But } AE = 2\,CQ \therefore \phi = 2\,\theta.$$

Now ϕ cannot be equal to $2\,\theta$ unless P coincides with E in the line A E; in which case the diameter E A D is the path of P.

74. It will be remembered that the hypocycloid determines the flank of the tooth upon either wheel: if, therefore, the radius of the circle describing the hypocycloid be taken in each case to be half that of the corresponding pitch circle, the teeth will have straight, or radial flanks, as they are commonly called.

The method of setting out the teeth is the following:—

Fig. 97.



Let A and B be the centres of two pitch circles which touch in the point D. (Fig. 97.)

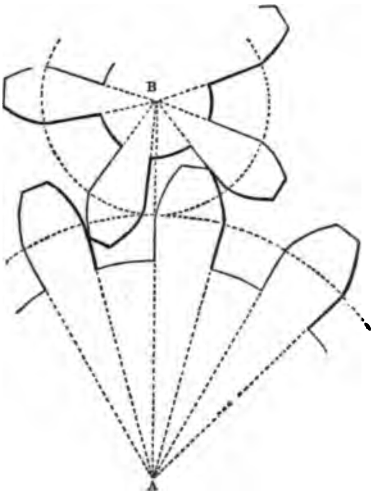
Let a circle, F, whose diameter is equal to B D, roll upon the circle A, and generate the epicycloid Q P; this curve determines the form of the driving surface of the teeth to be placed upon A.

Let a circle, G, whose diameter is equal to A D, roll upon the circle B, and generate the epicycloid $q\,p$; this curve determines the driving surface of the teeth to be placed upon B.

Here of necessity the describing circle is not of the same size when tracing out the points of the teeth upon A and B; but, by reason that the same circle gives the point upon A and the flank upon B, the condition in Art. 68 is still fulfilled.

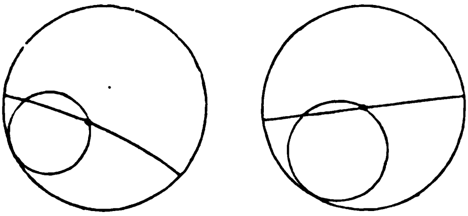
75. In each case the flanks of the teeth are straight lines pointing to the centres of the pitch circles: the form of the teeth is given in the annexed sketch. (Fig. 98.)

Fig. 98.



76. If we trace the changes in form of the hypocycloid, as the describing circle increases in size till it becomes

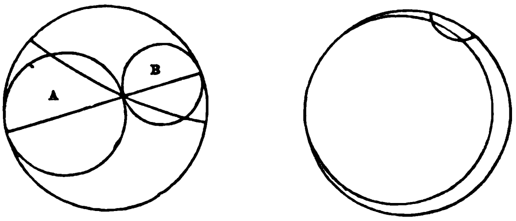
Fig. 99.



equal to that of the circle within which it is supposed to roll, we shall find that the curve gradually opens out

into a straight line (Fig. 99): that it then closes up again, and finally degenerates to a point. (Fig. 100.)

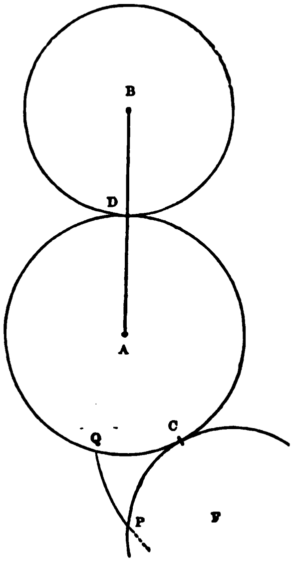
Fig. 100.



It will also appear that the same hypocycloid is generated by each of the circles A and B, which are so related that the sum of their diameters is equal to the diameter of the circle in which they roll.

77. The second particular case of the general solution occurs when the hypocycloid degenerates to a point; we then obtain a wheel with pins in the place of teeth, and derive a form which is extensively used in clockwork.

Fig. 101.



The pin must have some sensible diameter, but we will first suppose it to be a mathematical point.

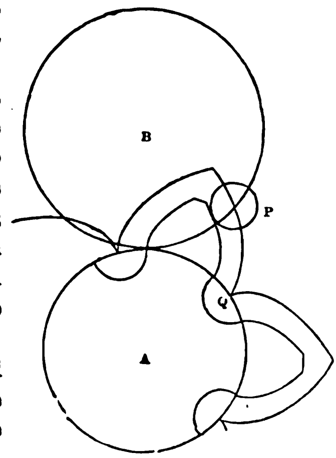
We have just seen that when the hypocycloid becomes a point, the describing circle must be equal to that within which it is supposed to roll. As before, let A and B be the centres of the two pitch circles touching in the point D. (Fig. 101.)

Let a circle, F, equal to B, *roll upon* the circle A, and generate the epicycloid P Q.

This curve will determine the acting surface of the teeth to be placed upon A: and here again the condition in Art. 68 is fulfilled.

78. To take into account the size of the pin, we proceed thus:

Fig. 102.

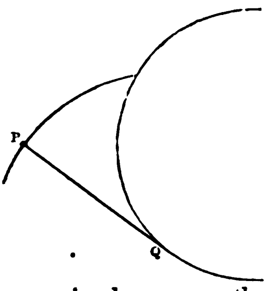


Let Q P (Fig. 102) represent the acting surface of a tooth which drives before it a point, P.

Make P the centre of a circle equal to the size of the pin: suppose this circle to travel along P Q, having its centre always in the curve; remove as much of the tooth as the circle intercepts, and the remainder will give the form of the working teeth.

We shall presently find that in practice the pins are always placed upon the driven wheel.

79. Another solution is derived from a property of the involute of a circle.

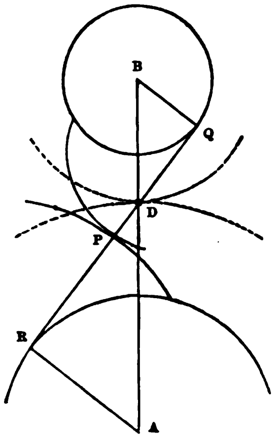


This curve is generated by a describing point, P, at the end of a string, P Q, which is kept stretched, and is unwound from the circumference of a circle. (Fig. 103.)

From the mode of generation it is quite evident that the tangent at any point, P, of the curve is $\perp^r$ to P Q, the string in any position, and we proceed to show that this form of curve fulfils in a very simple manner the requirements of Art. 68.

Let the involutes of two circles of any size be formed, and let them be brought into contact, as in Figure 104.

Fig. 104.

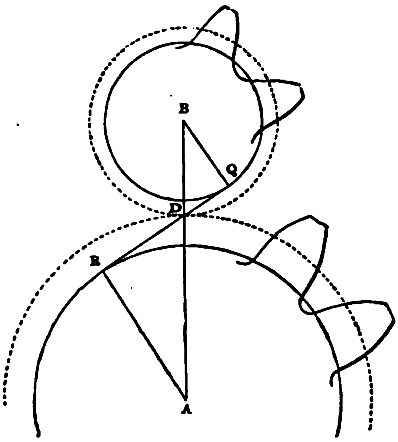


The common tangent at P must be perpendicular to both P Q and P R, or Q P R must be a straight line.

Now Q P R is a common tangent to the two circles, and will therefore cut the line of centres, A B, in a fixed point, D; but Q P R is also a common $\perp^r$ to the surfaces of the two teeth; hence the condition in Art. 68 is satisfied, and the pieces fitted with involutes of circles will move as if the circle of radius A D, were to roll upon the circle of radius B D.

80. In constructing teeth upon this principle a great latitude is introduced from the circumstance that A D and B D may remain constant while A R and B Q have different values. (Fig. 105.)

Fig. 105.



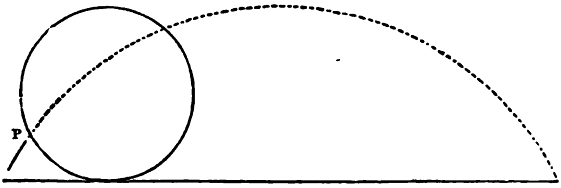
But after values have been assigned to A D and B D, we proceed to select some angle, R D A, at which to draw the line R Q, and the perpendiculars A R, B Q will then give the circles whose involutes determine the form of the teeth upon A and B.

In teeth of this kind there is no difference in shape between the point and the flank.

81. It remains to apply the above solutions to the cases where a pinion drives a rack, or conversely.

In this case one of the pitch circles becomes a straight line, or has an infinite radius, and the curve which is traced out by a point, P, in a circle rolling upon it, is called a cycloid, and is given in Figure 106.

Fig. 106.

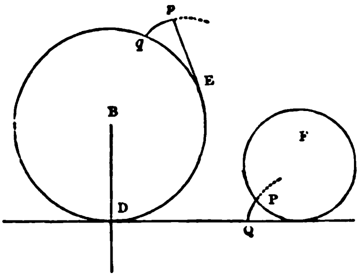


The solution in Art. 71 is so far modified that the teeth in the rack are formed by cycloids, those in the pinion being the same as before.

The solution in Art. 74 becomes more altered in character; for here the describing circle which generates the curve of the teeth suitable for the acting surfaces upon the rack is also infinite.

Referring to Art. 74, the circle F, rolling upon a straight line, generates a cycloid and gives the form of the driving surfaces of the teeth upon the rack: the circle G becomes infinite, and E p changes to a straight line. The changes which Fig. 97 undergoes being exhibited in Fig. 107, it is very apparent that the curve $q\ p$ passes into the involute of a circle, or that the

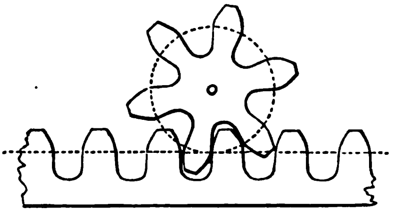
Fig. 107.



driving surfaces of the teeth upon the pinion become the involutes of a circle.

The form of the teeth in the rack and pinion is shown in Figure 108, the flanks in each case being straight lines.

Fig. 108.



82. The solution in Art. 77 changes as follows:

Fig. 109.

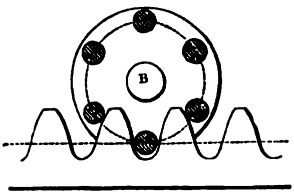
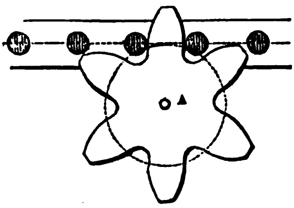


Fig. 110.



Let the circle A become infinite; then the curve, P Q, passes into a cycloid; so that the teeth upon the rack are cycloidal, as in Fig. 109.

Here the rack drives the pinion, but it may happen that the pinion drives the rack.

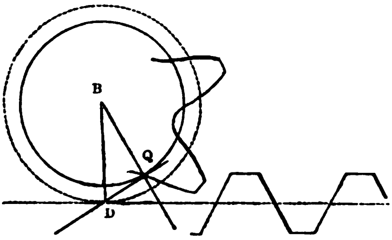
Now the pins are always to be placed upon the follower and not upon the driver, and as a consequence the circle B, in Fig. 101, becomes infinite, C P changes to a straight line, and P Q to the involute of a circle.

The annexed sketch (Fig. 110) gives the result of the proposition, and shows the pinion driving the rack.

The solution in Art. 79 changes if the circle A becomes infinite; in that case the involute of the infinite circle of radius AR is a straight $\perp^r$ to its circumference, or $\perp^r$ Q D. Hence

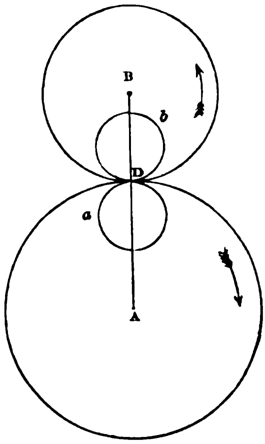
the teeth of the rack are straight lines $\perp^r$ to the direction of Q D. The direction of D Q is arbitrary; but when it has once been assumed, the radius B Q will be determined, and the involute teeth can be formed upon B, the teeth of the rack being straight lines inclined to the pitch line at an angle B D Q. (Fig. 111.)

Fig. 111.



83. There are now sundry general points for consideration. We may inquire, where does the action of two teeth begin, and where does it leave off?

Fig. 112.



Referring to the solution in Art. 71, we observe that if the motion take place in the direction of the arrows, and the describing circle be placed so as to touch either pitch circle in D, the contact of two teeth commences somewhere in *a* D, travels along the arc *a* D *b*, and ceases somewhere in D *b*.

Since *a* D (Fig. 112) lies entirely without the pitch circle B, it is clear that the action in *a* D is due solely to the fact that the teeth upon B project beyond the pitch circle B, and similarly that the action in D *b* depends upon the projections or *points* of the teeth upon A.

It is further evident that the greater the number of teeth upon the wheels, the closer is their resemblance to the original pitch circles, and the more nearly their action is confined to the neighbourhood of the point D.

By properly adjusting the amount to which the teeth are allowed to project beyond the pitch circles, and also their numbers, we can assign any given proportion between the arcs of contact of the teeth upon either side of the line A D B.

Where the teeth upon B are pins, there is comparatively very little action before the line of centres, and there would be none at all if the pins could be reduced to mere points, as in that case there would be nothing projecting beyond the pitch circle B.

84. It will be proved when we treat of rolling curves that the surface of one tooth must always slide upon that of another in contact with it, except at the moment when the point of contact is passing the line of centres.

This matter should be well understood, the teeth are perpetually rubbing and grinding against each other; we cannot prevent their doing so; our rules only enable us so to shape the acting surfaces that the pitch circles shall roll upon each other.

Nothing has been said about the teeth rolling upon each other; it is the pitch circles that roll; the teeth themselves slide and rub during every part of the action which takes place out of the line of centres.

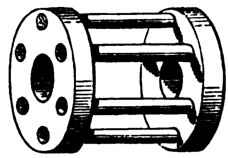
Since, then, the friction of the teeth is unavoidable, it only remains to reduce it as much as possible, which will be effected by keeping the arc of action of two teeth within reasonable limits.

Generally, the friction before a tooth passes the line of centres, is more injurious than that which occurs after the tooth has passed the same line: the difference between drawing a walking-stick along the ground after you and pushing it before you, is given by Mr. Denison as an illustration of the difference between the friction before and after the line of centres; but this difference is less appreciable when the arc of contact is not excessive.

Where a wheel drives another furnished with pins instead

of teeth, the friction nearly all occurs after the line of centres; hence such pin wheels are very suitable for the pinions in clockwork.

Fig. 113.



There is a very old form of the pin wheel, called a lantern pinion, which is shown in the diagram (Fig. 113), and which possesses the merit of great strength and durability.

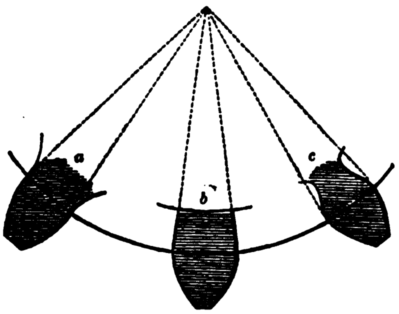
85. Again, since the line D P in Art. 70 is a $\perp^r$ to the surfaces in contact at P, it follows that the more nearly D P remains $\perp^r$ A D B, the less will be the loss of force transmitted between the wheels.

Here we have an additional reason for keeping the arc of contact as close as possible to the point D; there is a sensible loss of power as soon as the line D P differs appreciably from the direction $\perp^r$ to A B.

It is on this account that involute teeth are not used in machinery calculated to transmit great force: the line P D Q in Art. 79 is always inclined to the line A D B at a sensible angle, and a direct and useless strain upon the bearings of the wheels is the result.

86. As regards the strength of the teeth, we remark that

Fig. 114.



this quality is influenced by the size of the describing circle.

If the diameter of the describing circle be less than, equal to, or greater than the radius of the pitch circle, we shall have the flanks as shown in the sectors *a*, *b*, *c* of the sketch. (Fig. 114.)

It is evident that a small describing circle makes the teeth strong, and that it would be unwise to have them weaker than they are with radial flanks. The form of involute teeth being somewhat similar to that of a wedge, the teeth of this character are usually abundantly strong.

87. In combinations of wheel-work, the accurate position of the centres must be strictly preserved ; all the solutions given above, with one exception, entirely fail if there be any error in centreing the wheels ; they are totally vitiated if anything arises to deprive them of their geometrical accuracy. The exception occurs with involute teeth : the position of the centres determines the sum of the radii of the pitch circles, and the wheels will work accurately as long as the teeth are in contact at all.

We see too that teeth with radial flanks are not suitable for a set of change wheels ; the describing circles are derived from some given pair of pitch circles, and cannot be adapted to a different pair.

Where, however, the solution in Art. 71 is employed, the describing circle may be made the same for any number of pitch circles, and in that case any pair of wheels will work truly together.

88. The teeth upon *bevil wheels* are formed by a method due to Tredgold.

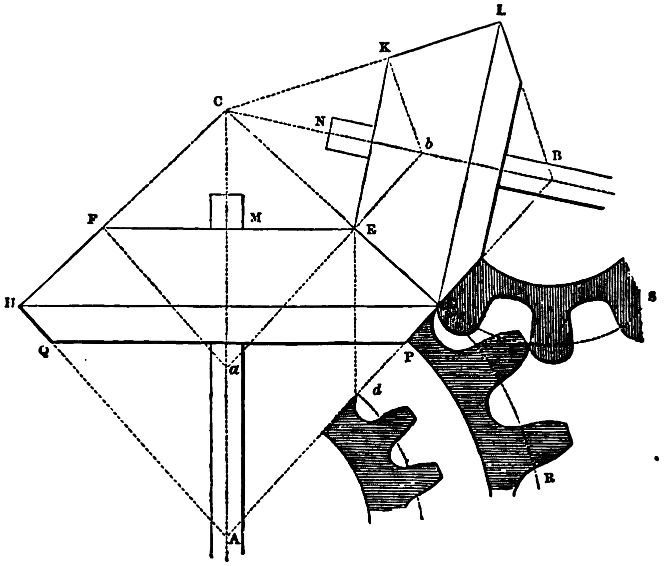
Let FEDH, KEDL (Fig. 115), represent the frustra of two right cones, whose axes meet in C, and which are therefore capable of rolling upon each other.

Let it be required to construct teeth upon two bevil wheels which shall move each other just as these cones move by rolling contact.

Draw ADB perpendicular to DE, meeting the axes of the cones in the points A and B.

Suppose the conical surfaces, H A D, B D L, to have a real existence, and to be flattened out into the circular segments

Fig. 115.



R, D S; these segments will roll upon each other just as the circular base H D rolls upon the circular base D L.

Hence these segments will serve as pitch circles, upon which teeth may be constructed by the previous rules: such teeth may be formed upon a thin strip of metal, and their outline can then be traced upon the surface of the cone terminating in A.

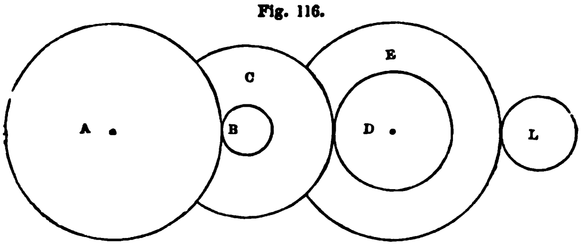
Similarly, if b E a be drawn $\perp^r$ to E D, the circle of radius A d = E a will be the pitch circle for the teeth upon the conical surface E a F; the teeth will taper from D to E, and the intermediate form will be determined by a straight line moving parallel to itself, and originally passing through the points D and E.

CHAPTER IV.

ON THE USE OF WHEELS IN TRAINS.

89. WHEN a train of wheels is employed in mechanism, the usual arrangement is that exhibited in Figure 116, where

Fig. 116.



two wheels of unequal size are placed upon every axis except the first and last.

Let A be the driver, L the extreme follower, and conceive that L makes (e) revolutions while A makes one revolution;

$$\text{then } e = \frac{\text{number of revolutions of L in a given time}}{\text{number of revolutions of A in the same time}}.$$

It will be convenient to distinguish (e) as the *value of the train*, and the ratio which it represents may be at once found when the numbers of teeth upon the respective wheels are ascertained.

Let A, B, C, D, &c., represent the numbers of teeth upon the respective wheels: the condition of rolling gives

$$\frac{\text{number of revolutions of B in a given time}}{\text{number of revolutions of A in the same time}} = \frac{\text{A}}{\text{B}};$$

and similarly for each pair of wheels:

$$\therefore e = \frac{\text{A}}{\text{B}} \times \frac{\text{C}}{\text{D}} \times \frac{\text{E}}{\text{F}} \times \text{\&c.} \ldots \frac{\text{K}}{\text{L}}.$$

We may frequently find it very convenient to regard (e) as positive or negative according as A and L revolve in the same or in opposite directions.

The comparative rotation of wheels is estimated in various ways, thus:

Let N, n be the numbers of teeth upon two wheels.
R, r their radii.
P, p their periods of revolution.
X, x the number of revolutions made by each wheel in the same given time.

It is easy to see that

$$\frac{N}{n} = \frac{R}{r} = \frac{P}{p} = \frac{x}{X} = e.$$

Cor. A belt and a pair of pulleys supply a mechanical equivalent for two working wheels: the belt may be open or crossed, and in either case

$$\frac{\text{the number of revolutions of B in a given time}}{\text{the number of revolutions of A in the same time}} = \frac{\text{diameter of A}}{\text{diameter of B}}.$$

The crossing of the belt merely reverses the direction of one of the pulleys.

Ex. Suppose that we have a train of five axes, and that

1. A wheel of 96 drives a pinion of 8.
2. The second axis makes a revolution in 12 seconds, and the third axis in 5 seconds.
3. The third axis drives the fourth by a belt and a pair of pulleys of radii 20 and 6 inches.
4. The fourth axis goes round twice while the fifth goes round three times.

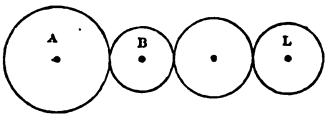
$$\text{Here } e = \frac{96}{8} \times \frac{12}{5} \times \frac{20}{6} \times \frac{3}{2} = 144$$

or the last axis makes 144 revolutions while the first axis goes round once.

90. It is very obvious that a wheel and pinion upon the same axis is a combination equivalent to a lever with unequal arms, and modifies the force which may be transmitted through it, and, further, that a single wheel is equivalent to a lever with equal arms, and produces no modification in the force which may pass through it.

So, therefore, when any number of wheels are in gear, as in Fig. 117, they are equivalent to a single pair of wheels, viz. the first A, and the last L; the intermediate wheels act as carriers only, and transfer the motion through the intervening space.

Fig. 117.



This also appears from the formula, where we find that

$$e = \frac{A}{B} \times \frac{B}{C} \times \frac{C}{D} \times \dots \frac{K}{L}$$
$$= \frac{A}{L}.$$

which is the same result as if A and L were alone concerned in the movement.

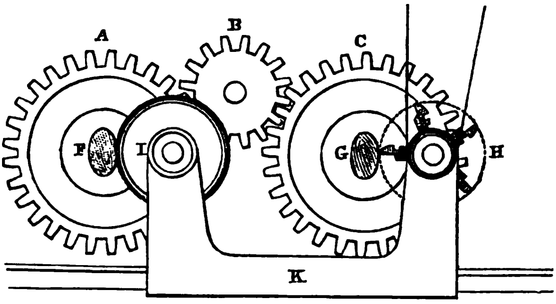
91. If, however, a single wheel, B, be interposed between two other wheels A and L, although B will not modify the force transmitted, nor alter the velocity, it may be useful in changing the direction in which L would otherwise revolve. An intermediate wheel so introduced is technically called an *idle wheel*, and we give an instance of its use for this particular purpose.

92. The Blanchard turning-lathe, of which a portion is shown in Fig. 118, is used for shaping the spokes of wheels, gun-stocks, shoe-lasts, and other objects of an irregular form.

It consists of two lathes, side by side, and parallel to

each other, the one containing the pattern, and the other a piece of wood out of which the article is to be formed. The pattern, F, of a spoke, for example, is made of iron of the exact size and shape required, and revolves slowly with the wheel, A; the motion of A is then carried on by the idle wheel, B, to a third wheel, C, of the same size as A,

Fig. 118.

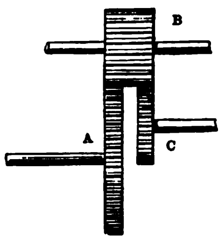


upon the axis of which is the unfinished spoke, and the function of this intermediate wheel is to cause the material to revolve in the same direction, and at the same rate as the pattern. A sliding frame, K, carries a tracing wheel, I, with a blunt edge, which is kept pressed against the pattern by a weight or spring, and also contains the cutters, H, which are driven at a speed of about 2,000 revolutions per minute by an independent strap.

The circle described by the extremities of the cutters is precisely the same size as the circle of the tracer, and it follows that the exact form which the tracer feels, as it were, upon the pattern, will be reproduced by the whirling of the cutters against the material, G, and that the spoke may be completed by giving a slow motion to the frame, H, in a direction parallel to the axis of the wheel, A. Sometimes the tracer and cutters are mounted upon a rocking frame, instead of upon a slide-rest, but the principle of the machine is not changed thereby.

93. An intermediate wheel may also be useful when two parallel axes are so close together that there is not space for the ordinary spur wheels. In such a case the axes A and C may be connected by a third wheel, B, and will of course revolve in the same direction.

Fig. 119.



The wheel, B, is elongated so as to gear with both A and C, and is called a *Marlborough wheel.* (Fig. 119.)

94. In designing toothed wheels, the following very simple equation connects the diameter of the pitch circle with the number of teeth and their pitch.

Let D be the diameter of the pitch circle in inches,
P the pitch of a tooth in inches,
n the number of teeth upon the wheel.

Then $n \cdot \mathrm{P}$ = circumference of pitch circle $= \pi\,\mathrm{D}$,

where $\pi = 3{\cdot}14159$, or $= \frac{22}{7}$ approximately.

$$\text{Hence } n = \frac{\pi}{\mathrm{P}} \cdot \mathrm{D}$$

$$\text{or} \quad \mathrm{D} = \frac{\mathrm{P}}{\pi} \cdot n.$$

In order to save trouble, definite values are assigned to P, such as $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$, $\frac{3}{4}$, $\frac{7}{8}$, 1, $1\frac{1}{8}$, $1\frac{1}{4}$, $1\frac{1}{2}$, 2, $2\frac{1}{2}$, &c., and the values of $\frac{\pi}{\mathrm{P}}$, $\frac{\mathrm{P}}{\pi}$ are calculated and registered in a table.

Thus, let $\mathrm{P} = 2\frac{1}{2}$ inches, we find in the table that

$$\frac{\pi}{\mathrm{P}} = 1{\cdot}2566 \text{ and } \frac{\mathrm{P}}{\pi} = {\cdot}7958.$$

Suppose a wheel of 88 teeth, and $2\frac{1}{2}$ inch pitch, to be in course of construction, and that we require to know the diameter of the pitch circle.

$$\mathrm{D} = \frac{\mathrm{P}}{\pi} \cdot n$$

$$= {\cdot}7958 \times 88 = 70{\cdot}03 \text{ inches.}$$

Or, again, if the diameter of the pitch circle be 70 inches, and the number of teeth of $2\frac{1}{2}$ inch pitch be required,

$$\begin{aligned} n &= \frac{\pi}{P} \cdot D \\ &= 1{\cdot}2566 \times 70 = 87{\cdot}96 \\ &= 88 \text{ very nearly.} \end{aligned}$$

In practice it is more easy to treat of the subdivision of a straight line than of the circumference of a circle, and it is the custom therefore to suppose the diameter of the pitch circle to be divided into as many equal parts as there are teeth upon the wheel, and to designate $\frac{D}{n}$ as the diametral pitch in contradistinction to P, the circular pitch.

Further, let $\frac{D}{n} = \frac{1}{m}$ where m is a whole number,

$$\text{now } \frac{D}{n} = \frac{P}{\pi} \therefore \frac{1}{m} = \frac{P}{\pi}, \text{ or } P = \frac{\pi}{m}.$$

The values of m and $\frac{\pi}{m}$ are registered in a table, of which a portion is given, and the circular pitch can be at once found.

Values of m	3	4	5	6	7	8	9	10	12
Values of P	1·047	·785	·628	·524	·449	·393	·349	·314	·262
or approximately	1	$\frac{3}{4}$	$\frac{5}{8}$	$\frac{1}{2}$	$\frac{7}{16}$	$\frac{3}{8}$	$\frac{11}{32}$	$\frac{5}{16}$	$\frac{1}{4}$

$$\text{Thus, let } D = 8 \text{ inches, } n = 80,$$

$$\therefore \quad \frac{D}{n} = \frac{8}{80} = \frac{1}{10}$$

$$\text{Hence} \quad P = {\cdot}314 = \tfrac{5}{16} \text{ inch.}$$

95. A common eight-day clock affords a familiar illustration of the employment of a train of wheels.

Figure 120 represents the disposition of the wheelwork in a clock of this character, and the various wheels are named in the sketch.

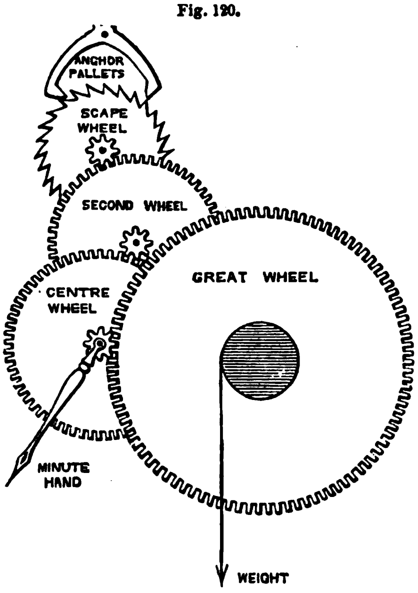
The great wheel turns round once in 12 hours, and may have 96 teeth: if then it engage with a pinion of 8 teeth on the axis or arbor of the centre wheel, this pinion will turn 12 times while the great wheel turns once, and is capable of carrying the minute hand.

Suppose the pendulum to swing 60 times in a minute, or to be a seconds pendulum, the scape wheel may have 30 teeth, and will be required to turn once in a minute.

Hence the value of the train from the centre to the scape wheel should be 60; if the pinions on the axes of the second and scape wheels have each 8 teeth, the centre and second wheels may have 64 and 60 teeth: in such a case

$$e = \frac{64 \times 60}{8 \times 8} = 60.$$

Fig. 120.



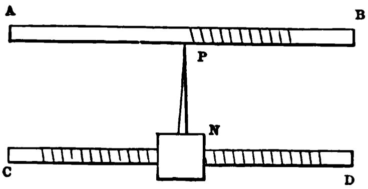
In order that the clock may go for 8 days, the great wheel must be capable of turning 16 times before the maintaining power is exhausted.

In a watch the balance wheel, which performs the function of a pendulum, makes at least 120 vibrations in a minute, and it is therefore desirable to introduce an additional wheel and pinion into the train.

96. The *Screw-cutting Lathe* is constructed upon the following principle:—

A B and C D (Fig. 121) are two parallel axes; a screw thread of a certain pitch is formed upon C D, and the slide rest, which carries the cutting tool, derives its motion from a nut placed upon C D.

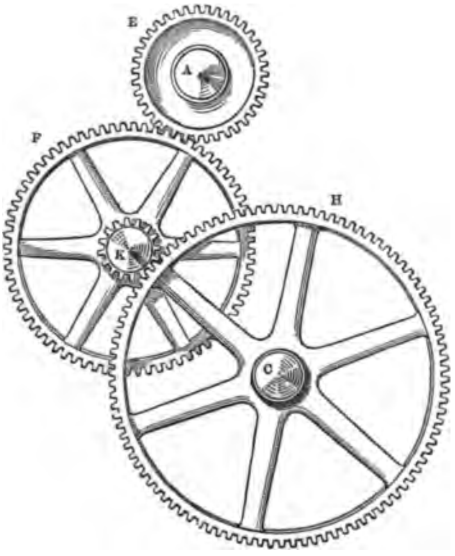
Fig. 121.



In the figure we suppose the nut N to carry a pointer, P, which may trace a screw thread upon A B.

Upon each revolution of C D the nut advances through a space equal to the pitch of the screw; if A B also revolve at the same rate

Fig. 122.



as C D, and in the same direction, the point P will describe

upon A B a screw thread exactly similar to that upon C D; if A B revolve more or less rapidly than C D, the pitch of the screw upon A B will be less or greater than that upon C D.

Generally, if A B make (m) revolutions for (n) revolutions of C D,

$$\frac{\text{pitch of screw on A B}}{\text{pitch of screw on C D}} = \frac{n}{m}.$$

The axes A B, C D are connected by a train of wheels, as shown in the diagram on page 91. (Fig. 122.)

Let E, F, K, H represent the numbers of the teeth upon the wheels so distinguished;

$$\text{Then } (e) \text{ the value of the train } = \frac{\text{E} \times \text{K}}{\text{F} \times \text{H}}$$

$$\therefore \frac{\text{pitch of screw upon A B}}{\text{pitch of screw upon C D}} = \frac{\text{E} \times \text{K}}{\text{F} \times \text{H}}.$$

A series of change wheels is furnished with a lathe, and a table indicates the wheels required for cutting a screw of any given number of threads to the inch. The screw upon C D having two threads in an inch, the numbers of teeth to be assigned to E, F, H, K are given in the table of which a specimen is subjoined.

No. of Threads per Inch.	E	F	K	H
12	90	90	20	120
$12\frac{3}{4}$	60	85	20	90
13	90	90	20	130
$13\frac{1}{2}$	60	90	20	90
$13\frac{3}{4}$	80	100	20	110
14	90	90	20	140

Ex. Let the pitch of the screw upon C D be $\frac{1}{2}$ an inch,

and let it be required to cut a screw of $\frac{1}{13}$ inch pitch upon A B, or a screw with 13 threads to the inch.

$$\text{Here } e = \frac{2}{13}$$

which is satisfied in the following manner:—

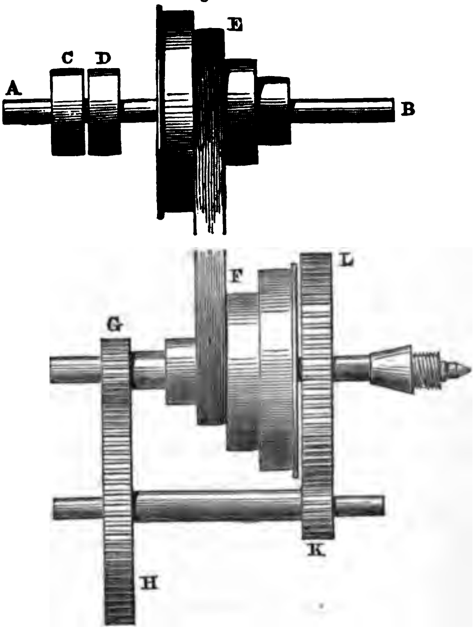
$$\frac{\text{E} \times \text{K}}{\text{F} \times \text{H}} = \frac{90 \times 20}{130 \times 90}$$

The guiding screw being right-handed, the above arrangement is suitable for cutting right-handed screws.

To cut a left-handed screw it is essential that A B and C D shall revolve in opposite directions.

Now A B revolves with the mandril of the lathe, and therefore the direction of the rotation of C D must be reversed; this is effected by interposing an idle wheel between H and K, which reverses the motion of the guide screw, C D, and makes the nut travel in the reverse direction. There is a double slot or groove upon the arm which carries K, in order to allow the adjustment of this idle wheel.

Fig. 123.

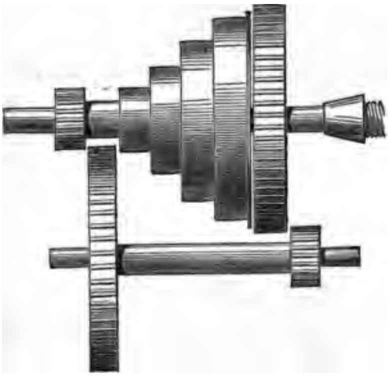


97. The contrivance sketched in Fig. 123 is found in every large lathe, and is useful in

other machinery where it is required to obtain increased power or a diminished speed. It enables the mechanic to change from a higher to a lower velocity, and gives another simple example of the use of wheels in trains.

A B is a shaft overhead, provided with a cone pulley, E, and fast and loose pulleys at C, D, to receive the power from the engine: a cone pulley F, similar to E, is fitted on the spindle of the lathe, and rides loose upon it; to this cone is attached a pinion G, which drives a wheel H, and so the motion is communicated by the pinion K, to the wheel L, which is fastened to the mandril of the lathe, and turns with it. The result is that the wheel L revolves much more slowly than the cone pulley F, and that the speed of the mandril is reduced by the multiplier $\frac{G \times K}{H \times L}$, where G, K, H, L represent the numbers of teeth upon these wheels respectively.

Fig. 124.



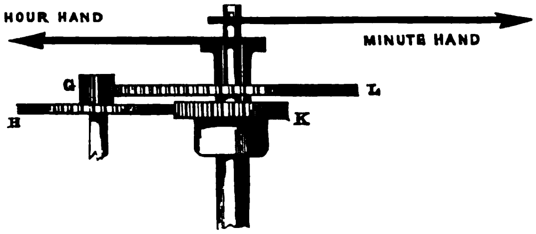
Where the lathe is worked at ordinary speeds, the wheels H and K are pushed out of gear in the manner shown in Fig. 124, and the cone pulley, F, is fastened to L by a pin, which can be removed when the slow motion is in operation.

98. It may be that the arrangement just examined has been borrowed from the watchmakers, for it is precisely the same as that employed to convey the motion from the minute to the hour hand of a watch or clock.

In a clock the minute hand is fastened to the arbor or axis of the centre wheel, and the hour hand is attached to a pipe which fits upon this axis, and derives its motion

from the minute hand; it is essential therefore to connect the pipe and axis by a train of wheels which will reduce the velocity in the ratio of 1 to 12.

Fig. 125.



The drawing (Fig. 125) is taken from a small clock, and represents the train of wheels employed. The pinion K, attached to the axis of the minute hand, drives H, whence the motion passes through G to L, and thus to the hour hand, which is fastened to the pipe on which L is fitted, and which corresponds to the mandril of the lathe. The value of e in the train is given by the equation

$$e = \frac{K \times G}{H \times L} = \frac{28 \times 8}{42 \times 64} = \frac{1}{12}.$$

99. The problem of connecting two axes by a suitable intermediate train of wheels may in some cases prove extremely troublesome, and may demand a considerable amount of arithmetical ingenuity.

The value of e being assigned as a fraction, the only thing to be done is to resolve the numerator and denominator into their prime factors, and then to compose the best train which may suggest itself.

If any of the factors appear unmanageably large, we may approximate to the value of e by continued fractions, and seek other factors which present less difficulty. If the value of e be an integer, it must still be split up into factors, and be further multiplied and divided by the numbers of teeth in each pinion.

Thus, suppose that two axes are to be connected whereof one revolves in 24 hours, and the other in 365 days 5 hours 48 minutes 48 seconds, as in Mr. Pearson's orrery,

Since 24 hours = 86400 seconds,

and 365 days 5 hrs. 48 min. 48 sec. = 31556928 seconds,

$$\therefore e = \frac{31556928}{86400}$$

$$= \frac{164359}{450}$$

$$= \frac{269 \times 47 \times 13}{10 \times 9 \times 5}.$$

Here 269 is an inconveniently large number, and 5 is certainly too small.

The wheel of 269 teeth cannot be got rid of without altering the entire ratio, but the pinions of 9 and 5 teeth may be changed into others of 18 and 10 teeth.

Thus we have $e = \dfrac{269 \times 26 \times 94}{10 \times 10 \times 18}$.

Those who have approximated to e by an algebraical process have derived the fraction

$$\frac{94963}{260} = \frac{11 \times 89 \times 97}{4 \times 5 \times 13}$$

$$= \frac{44 \times 89 \times 97}{8 \times 10 \times 13}$$

which avoids the high number 269, and corresponds to a period of 365 days 5 hours 48 min. 55·38 sec.

If e be an integer, as 720 for example,

$$e = 10 \times 9 \times 8$$

$$= \frac{80 \times 72 \times 64}{8 \times 8 \times 8}$$

which gives a probable solution for the train.

It is also a matter of inquiry to ascertain the smallest number of axes concerned in the transmission of any required motion.

The smallest number of teeth which are to be allowed upon a pinion must be given, as well as the largest number to be allowed upon any wheel.

Suppose that no pinion is to have less than 6 teeth, and no wheel more than 60, and let us trace the values of e.

With two axes $e = \frac{60}{6} = 10$.

If the numerator be diminished, or the denominator be increased, the resulting value of e is lessened, or, in other words, 10 is the greatest possible value of e when two axes are employed.

With three axes the greatest value of e is $\frac{60 \times 60}{6 \times 6}$ or 100, and with four axes it is 1000, and so on.

Let e have some value between 10 and 100, we now find that three axes will suffice, and that each wheel must have less than 60 teeth in order to reduce e from 100 to 60.

$$\text{Thus } e = \frac{48}{6} \times \frac{45}{6} = 60.$$

Again, let $e = \frac{365}{3} = 121\frac{2}{3}$, and suppose 180 and 12 to be the limiting numbers of teeth upon a wheel and pinion respectively, in the train which is about to be composed.

$$\text{Then } \frac{180}{12} = 15$$

$$\text{and } \quad \frac{180}{12} \times \frac{180}{12} = 15 \times 15 = 225.$$

Now $121\frac{2}{3}$ is less than 225, and therefore three axes will suffice, as in the train represented by

$$e = \frac{180}{18} \times \frac{146}{12}$$

Generally, let p be the least number of teeth upon a pinion, w the greatest number upon a wheel, x the number of fractions in e, then the greatest possible value of e will be given by the equation

$$e = \left(\frac{w}{p}\right)$$

$$\text{whence } \log e = x\,(\log w - \log p)$$

$$\therefore x = \frac{\log e}{\log w - \log p}$$

x will probably be a fraction, in which case the next integer greater than $x + 1$ will represent the required number of axes.

Ex. $\quad$ Let $e = \frac{365}{3}$, $w = 180$, $p = 12$,

$$\therefore \frac{w}{p} = 15 \quad \therefore x = \frac{\log 365 - \log 3}{\log 15}$$

$$= 1 + \text{a fraction.}$$

Now the integer next greater than $x + 1$ is 3, or 3 axes will be required.

We observe that it is not necessary to find the actual value of x, but simply to ascertain the integer next greater than it.

Next let a wheel of A teeth drive one of B teeth where A is greater than B, and let $\frac{A}{B} = \frac{a}{b}$ in lowest terms.

1. Let it be required to bring the same teeth into contact *as often* as possible.

Since this contact occurs after b revolutions of A or a revolutions of B, we shall effect our object by making a and b as small as possible, that is, by providing that A and B shall have a large common measure.

Ex. $\quad$ Let A $= 72$, B $= 24$,

$$\text{then } \frac{a}{b} = \frac{72}{24} = \frac{3}{1}$$

or the same pair of teeth will be in contact after three revolutions of B, or one revolution of A.

2. Let it be required to bring the same teeth into contact *as seldom* as possible.

Here we must try and prevent A and B from having any common measure at all.

Ex. As before, let $A = 72$, $B = 24$,

Now change A to 73, and we shall still have $\frac{A}{B} = 3$ very nearly, or the relative angular velocity of A and B will be scarcely distinguishable from what it was originally. But the alteration will effect what we require, for now $\frac{A}{B} = \frac{73}{24}$ which is a fraction in its lowest terms; there will therefore be a contact of the same pair of teeth only after 73 revolutions of B, or 24 revolutions of A.

The insertion of a tooth in this manner was an old contrivance of millwrights to prevent the same pair of teeth from meeting too often, and was supposed to ensure greater regularity in the wear of the wheels; the tooth inserted was called a *hunting cog*.

The clockmakers, on the contrary, appear to have adopted the opposite principle.

Finally, we would remind the reader that everything which we have said here about wheels in trains is true, whatever be the directions of their axes; we only care to know the relative sizes of the pitch circles, and the directions in which they turn; any part of the train may be composed of *bevil wheels* without affecting our results.

CHAPTER V.

AGGREGATE MOTION.

100. We have seen that every case of the curvilinear motion of a point is of a compound character, resulting from the superposition of two or more rectilinear motions.

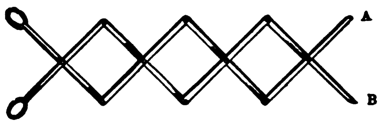
It often happens in machinery that some revolving wheel or moving piece becomes the recipient of more than one independent motion, and that such different movements are concentrated upon it at the same instant of time.

The motion is then of a compound or *aggregate* character, and we propose to classify under the head of Aggregate Motion a large variety of useful contrivances.

We may commence with two or three very simple examples.

The well-known frame called *Lazy Tongs* is a contrivance depending upon aggregate motion.

Fig. 126.



The rapid advance of the ends A and B is due to the fact that these points are the recipients of the sum of the resolved parts of the circular motion which takes place at each angle.

101. The *differential screw* is another instance, and is a favourite with writers on mechanics, inasmuch as it gives theoretically a mode of obtaining an enormous pressure by the action of a comparatively small force.

It is constructed upon the following principle: two screw threads of different degrees of inclination are formed upon the same spindle A B (Fig. 127), the spindle itself passing

through two nuts whereof one, E, is part of a solid frame; and the other, D, can slide in a groove along the frame. Let P Q, represent the pitches of the screws at E and D;

Fig. 127.

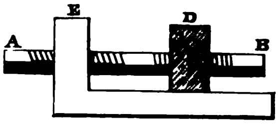
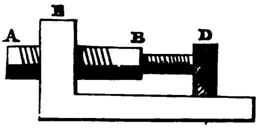


Fig. 128.

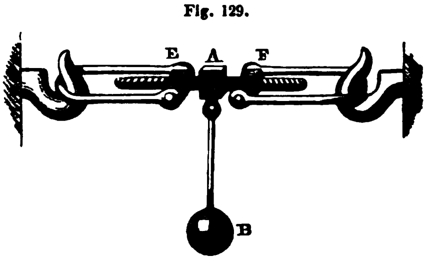


then upon turning A B once the nut D is carried forward through a space P, and is brought back again through a space Q; it therefore advances through the difference of these intervals.

There is a form of the differential screw described in the fifteenth volume of the 'Philosophical Transactions,' which is known as *Hunter's Screw.* Here one screw is a hollow tube acting as a nut for the second screw in the manner shewn in Fig. 128; the smaller screw is attached to a piece D sliding in the frame, and is not allowed to rotate; upon turning the screwed pipe A B, the piece D will move through a space equal to the difference of the pitches of the two screw threads.

If one screw thread were right-handed and the other left-handed, the nut would travel through a space, P + Q, upon each revolution.

Fig. 129.



A right and left-handed screw are often used in combination, for the purpose of bringing two pieces together. There is a very common instance in the coupling which connects two railway carriages. (Fig. 129.) Upon turning the arm

A B, the screws which are moved by it bring the nuts E and F at the ends of the coupling links closer together, or cause them to separate. This is obviously a most convenient arrangement.

102. Another contrivance for lifting heavy weights by a small expenditure of power is the *Chinese Windlass.*

Fig. 130.

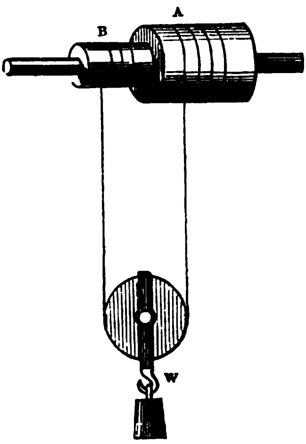


Fig. 131.

Here a rope is coiled in opposite directions round two axles A and B, of unequal size; the rope is consequently unwound from one axle while it is being wound up by the action of the other. (Fig. 130.)

Let R, r be the radii of the axles, then W moves through π (R $-$ r) upon each revolution of the axles.

The length of string required for each revolution is moreover 2 π (R + r) and is so large that the contrivance is practically of little value.

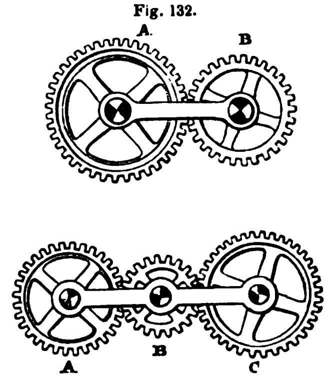
The object of *Weston's Differential Pulley-block* is to avoid this difficulty about the expenditure of rope. In the

Chinese Windlass, one end of the rope is supposed to be fastened to the axle A, and the other end to the axle B; if, however, these two ends were brought together, the supply of rope necessary for B might be drawn from that coiled upon A, and the expenditure would be really $2\pi(R - r)$. There would be many inconveniences attending this arrangement in practice, but it has been put into a working shape by Mr. Weston. In his pulley-block (Fig. 131), there are two pulleys A and B, nearly equal in size, turning together as one pulley, and forming the upper block; an endless chain supplies the place of the rope, and must of course be prevented from slipping by projections which catch the links of the chain. The power is exerted upon that portion of the chain which leaves the larger pulley, the slack hangs in the manner shown in the sketch, and the chain continues to run round till the weight is raised; the combination is therefore highly effective.

103. The subject of *Epicyclic trains* will now occupy our attention, and we shall discuss some of the most useful applications of that peculiar arrangement of wheelwork which is technically so designated.

An epicyclic train differs from an ordinary train in this particular: the axes of the wheels are not fixed in space, but are attached to a rotating frame or bar, in such a manner that the whole train of wheels can derive motion from the revolutions of the bar.

Fig. 132.



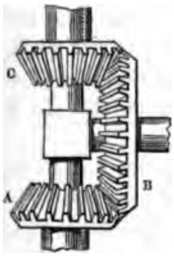
There are certain fundamental forms which consist of trains of two or three wheels; the first wheel of the train is usually concentric to the revolving arm, and the last wheel may be so likewise.

These elementary forms are exhibited in the annexed diagrams, and the peculiarities which result from compounding any independent motion with that which arises from the rotation of the arm will demand some careful and attentive study.

In Figure 132 the wheel B, or the wheels B and C, are attached to a bar which is capable of revolving about the centre of the wheel A, the axis of this latter wheel being fixed in space.

In Figure 133, we have a combination of three bevil wheels, whereof the axes of A and C are identical and fixed in space, and the wheel B is carried round upon an arm which supports it.

Fig. 133.



It should be understood that any number of intermediate wheels may exist between the first and last wheels of the train, and that the wheels in the train may derive the whole of their motion from the arm, or they may receive one portion from the arm and the remainder from an independent source.

104. Let the arm make a revolutions, the first wheel A make m revolutions, the last wheel C make n revolutions, during the same period of time, and let e (Art. 89) be the *value* of the train. Then the first wheel makes $(m - a)$ revolutions relatively to the arm, and the last wheel makes $(n - a)$ revolutions relatively to the same arm;

whence it follows that $e = \dfrac{n - a}{m - a}$

There are three cases to consider:—

1. Let A be fixed or $m = 0$.

$$\therefore e = \frac{n - a}{-a} = -\frac{n}{a} + 1$$

$$n = a\,(1 - e) \text{ and } a = \frac{n}{1 - e}$$

2. Let C be fixed or $n = 0$.

$$\therefore e = \frac{-a}{m-a}$$

$$\therefore m = a\left(1 - \frac{1}{e}\right) \text{ and } a = \frac{m\,e}{1-e}$$

3. Let neither of the wheels be fixed.

Then $m\,e - a\,e = n\,a$

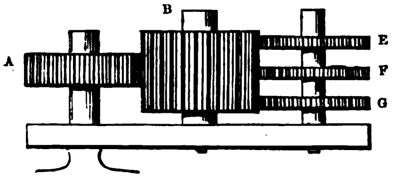
$$\therefore a = \frac{m\,e - n}{e-1} = \frac{m\,e}{e-1} + \frac{n}{1-e}$$

that is to say, the number of revolutions of the arm is the aggregate of the separate revolutions which it would have received in the two former cases.

105. *Ferguson's Paradox* is obtained by placing three wheels upon the axis which usually carries C, and making these wheels very nearly equal to each other and very nearly equal to A.

Thus let A have 20 teeth, and the numbers of teeth upon E, F, G, be 21, 20, 19 respectively. (Fig 134.)

Fig. 134.



The number of teeth upon B is immaterial.

For the wheel E we have $e = \frac{20}{21}$ which is less than unity.

$$\therefore \frac{n}{a} = 1 - \frac{20}{21} = \frac{1}{21} \text{ and is positive.}$$

2. For the wheel F; $e = \frac{20}{20} = 1 \therefore \frac{n}{a} = 0.$

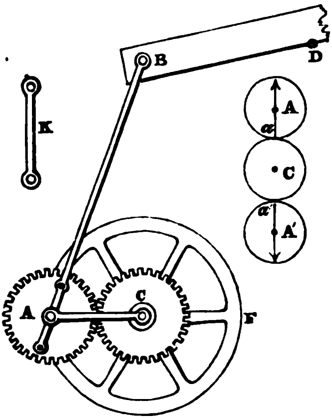
3. For the wheel G; $e = \frac{20}{19}$

$$\therefore \frac{n}{a} = 1 - \frac{20}{19} = -\frac{1}{19} \text{ and is negative.}$$

So that when the arm is made to revolve round A fixed in space, the wheel E turns slowly in the same direction as the arm, F remains at rest, and G moves slowly in the reverse direction.

106. The *Sun and Planet Wheels* were invented by Watt, and were used to convert the reciprocating motion of the working beam of an engine into the circular motion of the fly wheel, we have already referred to this invention in Art. 4, and have explained the object which it was intended to fulfil. The sketch (Fig. 135) shows the general arrangement of the contrivance; B D is the working beam of the engine, oscillating about the point D, and a wheel A is fixed to the connecting rod B A in such a manner that it cannot rotate, though always in gear with another equal wheel C upon the axis of the fly-wheel. As the beam oscillates, the wheel A will run round C, and is prevented from leaving it by the link A C, which is shown separately at K, or otherwise by a pin at the back which moves in a groove upon the wheel F. Since it is provided that A shall not turn upon its axis, it follows that C must do so, or the teeth would be torn off, and indeed the rotation of C will be more rapid than we should at first imagine, for it will be found that C makes two complete revolutions upon its axis while A runs round it once.

Fig. 135.



We may explain the peculiarity as follows: if the discs

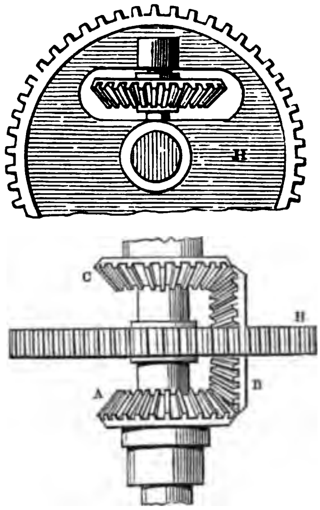
A and C were fastened together at the point a, and C were to make half a revolution, A would come into the position A′ and the direction of the arrow marked upon it would be reversed. But in the actual motion this arrow retains its first direction, and in order to recover it, the disc A′ must again rotate through 180°, and must carry C round through another half revolution; so therefore when we recur to the arrangement invented by Watt, C will make a complete revolution while A descends from the highest to the lowest position, or travels half way round it.

The same thing appears from the formula.

107. An illustration may now be taken from the cotton mills of Lancashire.

During the process of the manufacture of cotton yarn or thread, it is essential to wind the partially twisted fibre upon bobbins, and at the same time to protect it from any undue strain.

Fig. 136.



The fibre is delivered to the bobbins at a uniform rate, whereas the bobbins get larger as they fill with the material or *roving*, and hence the winding machinery must be so contrived that the rate of revolution of the bobbin shall slowly decrease upon the completion of each layer of the fibre.

In the year 1826 Mr. H. Houldsworth patented an invention which solves the problem of the *bobbin motion* in the most complete and satisfactory manner.

In the last case of Art. 103 we have supposed the wheel

B to be carried by an arm which is capable of revolution round the axis A C; the best way, however, of suspending B is to attach it to the face of a wheel, H, as in Figure 136.

Let this be done, and let A be connected with the driving shaft of the engine, so that the rotation of A shall necessarily be constant.

If now some independent motion be imparted to the wheel H, the result may be calculated from the formula.

Here A, B, C are equal in size,

$$\therefore \quad e = -1$$
$$\therefore n - a = a - m$$
$$\therefore n + m = 2a$$

which gives the analytical relation between the angular velocities of A, B, C.

As soon as we examine this formula, we shall comprehend that the velocity of C may be reduced by altering the velocity of H.

1. For let $a = m$, or let A and H turn at the same rate,

$$\text{then } n + m = 2a = 2m$$

$\therefore n = m$, or C has exactly the same motion as A.

2. Let $a = \frac{3m}{4}$ i.e. let H make three revolutions while A makes 4,

$$\therefore \quad n + m = 2 \times \frac{3m}{4} = \frac{3m}{2}$$

$\therefore n = \frac{m}{2}$ or C moves half as fast as A.

3. Let $a = \frac{m}{2}$ in which case H makes one revolution for two revolutions of A,

$$\therefore \quad n + m = 2 \times \frac{m}{2} \quad m$$

$\therefore \quad n = 0$, or C stops altogether.

We have taken extreme cases, from which it appears

that when the velocity of the arm is made less than that A, the velocity of C is reduced in a twofold degree.

Generally, let $a = m - \frac{m}{x}$

$$\therefore n = 2a - m$$

$$= 2m - \frac{2m}{x} - m$$

$$= m - \frac{2m}{x}$$

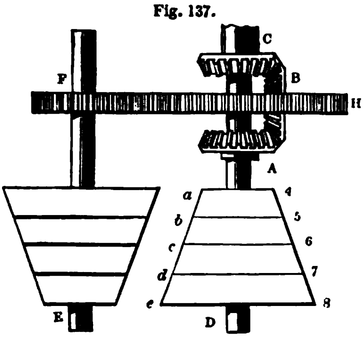
or the rate of diminution of n is twice that of a.

It now becomes easy to obtain any required reduction in the velocity of C; a reduction in the velocity of H must first be effected by shifting a driving strap along a conical pulley, and the velocity of C will be reduced exactly twice as much as that of H.

Mr. Houldsworth's invention consists, therefore, in imparting to the wheel C two independent motions which travel by different routes, and which, after combination in the manner just investigated, are capable of producing the desired *bobbin motion.*

108. In order to fix our ideas, let us calculate the motion in the following example:—

Fig. 137.



Suppose A, B, C (Fig. 137) to be three equal wheels, and that A is fixed to a shaft A D, which carries a conical pulley provided with steps at a, b, c, d, e, where the diameters are 4, 5, 6, 7, 8.

E F is another shaft carrying a second conical pulley which is the counterpart of the first, and terminating in a wheel F whose diameter is half that of H.

A crossed strap connects the two cones, and the axis A D is made to revolve with a uniform velocity.

It is required to reduce the motion of C when the strap is shifted along the conical pulley.

1. Let the strap be placed at a, the velocity of H will be $\frac{1}{4}$ that of A D.

$$\therefore a = \frac{m}{4} \text{ and } n = 2 \times \frac{m}{4} - m = -\frac{m}{2}$$

or C moves in the opposite direction to A, and with half its velocity.

2. Let the strap be at b, the vel. of H will be $\frac{5}{14}$, that of A D, $\left(\text{here } e = \frac{5}{7} \times \frac{1}{2} = \frac{5}{14} \text{ according to Art. 89.}\right)$

$$\text{or } a = \frac{5\,m}{14} \text{ and } n = 2\,a - m = \frac{5\,m}{7} - m$$

$$= -\frac{2\,m}{7}$$

or C still moves in the opposite direction to A, but less rapidly in the ratio of 2 to 7.

3. Place the strap at c;

$$\text{then } a = \frac{m}{2} \therefore n = 2 \times \frac{m}{2} - m = 0$$

or C stops altogether.

4. Place the strap at d; $\therefore a = \frac{7\,m}{5} \times \frac{1}{2} = \frac{7\,m}{10}$

$$\text{whence } n = 2\,a - m = \frac{7\,m}{5} - m = \frac{2\,m}{5}$$

i. e. C and A move in the same direction with velocities in the ratio of 2 to 5.

5. Finally adjust the strap at e, and the velocity of H will be the same as that of A D.

Here $a = m$, and $n = 2\,m - m = m$,
or the motion of C is precisely the same as that of A.

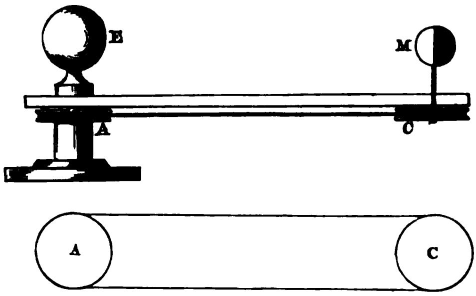
109. Numerous models intended to illustrate simple

astronomical problems connected with the motion of the heavenly bodies are formed upon the principle which is under discussion.

The subjoined arrangement exhibits mechanically the phases of the moon.

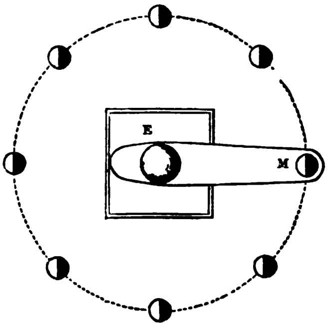
Here wheelwork is dispensed with; A and C are simple discs of wood connected by a gutta-percha band, as in the diagram. The band may be open or crossed, according as the discs are required to turn in the same or the opposite direction.

Fig. 138.



E is the earth (Fig. 138); a white ball M, fixed rigidly to the arm, represents the moon; a hemispherical black cap fits upon M, and is connected with the disc C, so as to move with it. If the cap is to represent the dark portion of the moon's surface, it must not rotate as the arm revolves, and this is clearly the case of the wheel F in Ferguson's Paradox; consequently A must be equal to C, and the band which connects A and C must not be crossed.

Fig. 139.

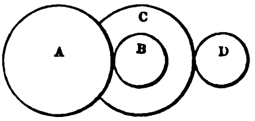


As the arm revolves, the disc C moves round in a circular path without at all rotating upon its own axis, and the hemispherical cap takes the various positions shown in Fig. 139, imitating thereby the shadow which would be caused by a luminous body at a great distance to the left of E.

110. Epicyclic trains may be employed to produce a very slow motion upon the following principle:—

Let A, B, C, D represent the numbers of teeth in a train of wheels in gear arranged as in Fig. 140.

Fig. 140.



If A = D, and B = C, then A and D will rotate with the same velocity in the same direction, but if the equality between (A, D) and (B, C) be slightly disturbed, we shall produce a small change in the *value* of the train.

Suppose, for example, that A is less than D,

or that A = 31, D = 32;

and, again, that B is less than C,

or that B = 125, C = 129;

then e, the *value* of the train, will be

$$= \frac{31 \times 129}{125 \times 32}$$

$$= \frac{3999}{4000}$$

Also the more nearly the equality is maintained between (A, D) and (B, C) the more nearly will the angular velocities of A and D be the same, or the more nearly will e be equal to unity.

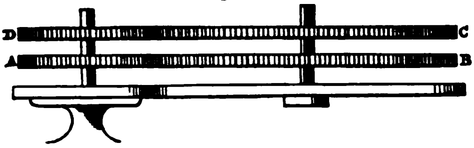
Thus if B = D = 100, A = 101, C = 99

$$\text{we have } e = \frac{101 \times 99}{100 \times 100} = \frac{9999}{10000}$$

Let us now arrange A, B, C, D in an epicyclic train, then the turning of the arm will set all the wheels in motion except A, which is fixed, and we shall have D and A moving

relatively to each other just as before, that is to say, D will turn very slowly over A at rest. (Fig. 141.)

Fig. 141.



Taking the formula $\frac{n}{a} = 1 - e$, and substituting for e the values given above,

we have in the first example $\frac{n}{a} = \frac{1}{4000}$

and in the second example $\frac{n}{a} = \frac{1}{10000}$

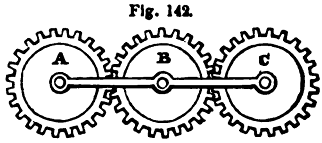
Hence the arm will make 4000 or 10,000 revolutions respectively while the wheel D turns round once.

111. This last example leads us to compare the movement of any wheel in an epicyclic train with that in another train where the axes are fixed in space.

Take a very simple case, such as that of three equal wheels, A, B, C. (Fig. 142.)

If the arm be fixed, and A makes one turn, the wheel C will also turn once in the same direction. But if the arm revolve round A fixed, the wheel C will apparently run round just as it did upon the last supposition, and yet at the end of a revolution of the arm it will be found that the wheel C has not turned at all.

Fig. 142.

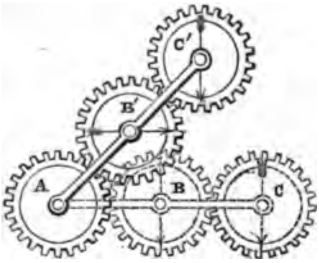


The explanation is that the fixed train gives the *absolute* motion of C due to its connection with A, whereas the epicyclic train exhibits the *relative* motion of C with regard to A.

The same thing is true with respect to any other wheel in the train such as B; thus when the axes are fixed in space, A and B revolve in opposite directions, and the motion of B relatively to A is twice its absolute motion: in an epicyclic train, on the other hand, it will be found that when the arm has made one revolution round A fixed, the wheel B has really turned twice.

This fact was made use of by Watt, in the construction of the sun and planet wheels, described in Art. 106.

Fig. 143.



The motions of the wheels B and C in an epicyclic train are shown in Fig. 143. The arm is supposed to have revolved through an angle of 45°; it will be seen that B has turned through a right angle, while C has not turned at all.

112. In the manufacture of rope the operation of 'laying,' or twisting the strands into a perfect rope, is effected by special machinery.

The Rev. Edmund Cartwright, the inventor of the power-loom, was also the first inventor of a machine for making rope. The general character of the contrivance will be understood from the sketch (Fig. 144), which is taken from the specification of the invention.

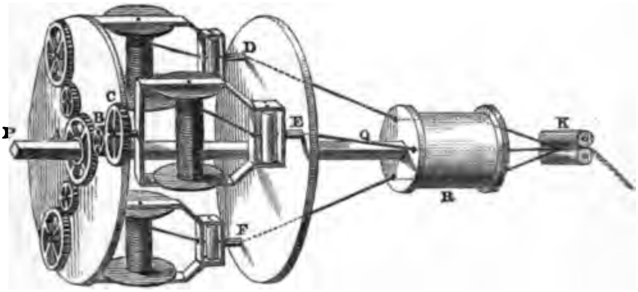
The machine itself is called a '*Cordelier*,' and consists of a frame placed upon a horizontal shaft P Q, and terminating in a laying-block R, which serves the double purpose of directing the strands to the rollers at K, where they are twisted into rope, and of forming a support or bearing for one end of the shaft.

Three spool frames carry the bobbins, or spools, which contain the supply of strands, and the strands, as they are unwound from the bobbins, pass through delivery rollers at *D, E, and F,* and thence onward to the laying top.

All this is simple enough, and might be the invention of anyone; but there is yet a difficulty to be overcome, which we proceed to explain.

Upon examining a rope it will be found that the twist of the rope is always in the opposite direction to that of the strands, and it follows that if the bobbins were absolutely fixed to the rotating frame the strands themselves would be untwisting during the whole operation. This untwisting is provided against in a rope-walk by the use of two machines, one at each end of the walk; the strands are attached to hooks on one of the machines, and these hooks are made to rotate with a velocity which exactly neutralises the twist of the machine which is forming the strands into a finished rope.

Fig. 144.



In the Cordelier the difficulty is at once removed by the introduction of an epicyclic train. A dead wheel A, so called because it is held stationary while the shaft P Q rotates within it, gears with a second wheel B, and this latter with a third wheel C, *equal* to A, whose axis terminates in one of the spool frames. Now we have just proved that in such a train C will run round A without rotating at all upon its own axis, and hence the bobbin may be carried round without in the slightest degree untwisting the strand.

113. In order to make this matter still more apparent, we refer the student to Fig. 145, which is intended to show three positions of a spool when rotating in a frame without

Fig. 145.

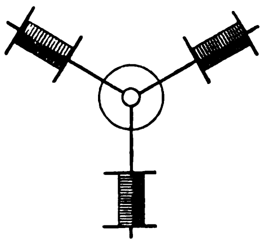
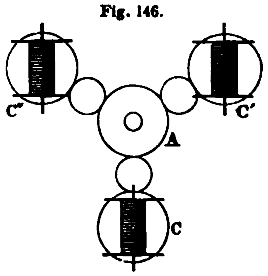


Fig. 146.



the intervention of an epicyclic train; it is quite evident that the spool has made one rotation round an imaginary axis through its centre while rotating once round the centre of the frame.

The same thing is true of the moon, which rotates once upon its axis while performing a complete revolution in its orbit round the earth, and the consequence is that the moon always turns the same face towards us, and that we see only one half of its surface.

In Fig. 146, on the other hand, where an epicyclic train, with C equal to A, is interposed, the bobbin will take the positions C, C′, C″, during a revolution, and the rotation just referred to will be exactly neutralised.

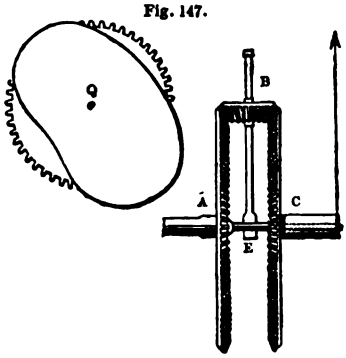
Captain Huddart has incorporated this invention of Cartwright into some very useful machinery for manufacturing rope, and has employed the same epicyclic train; but he has made C smaller than A in the proportion of 13 : 14, as in the case of the wheel G in Art. 105, and the result is that a slight additional twist is given to each strand in the act of laying it into rope.

114. Another illustration is found in *Equation clocks*. In these nearly obsolete pieces of mechanism the minute *hand points* to true solar time, and its motion therefore

consists of the equable motion of the ordinary minute hand plus or minus the *equation* or difference between true and mean solar time.

In clocks of this class the hand pointing to true solar time is fixed to the bevil wheel. (Fig. 147.)

Fig. 147.



The wheel A moves as the minute hand of an ordinary clock; the intermediate wheel B is fixed to a swinging arm E B, as in Art. 103, and the position of C will be in advance of that of A when E B is caused to rotate a little in the same direction, and behind that of A when E B is moved in the opposite direction.

Thus as C goes round during each hour of the day, the hand attached to it may be a few minutes before or behind another showing mean time, and deriving its motion at once from A.

The required motion of E B is obtained from a cam plate, Q, curved as in the diagram, and attached to a wheel which revolves once in a year.

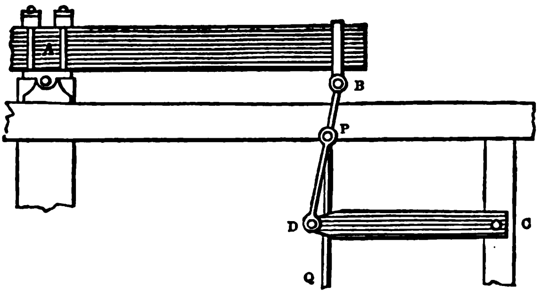
115. The *Parallel Motion* used in steam-engines was the invention of James Watt, and was thus announced in the specification of a patent which he obtained in the year 1784:—

'My second new improvement on the steam-engines consists in methods of directing the piston rods, the pump rods, and other parts of these engines, so as to move in perpendicular or other straight or right lines, without using the great chains and arches commonly fixed to the working beams of the engines for that purpose, and so as to enable the engine to act on the working beams or great levers both by pushing and by drawing, or both, in the ascent and

descent of their pistons. I execute this on three principles. . . . . The third principle, on which I derive a perpendicular or right-lined motion from a circular or angular motion, consists in forming certain combinations of levers moving upon centres, wherein the deviations from straight lines of the moving end of some of these levers are compensated by similar deviations, but in opposite directions, of one end of other levers.'

The annexed sketch in Figure 148 is copied from the original drawing.

Fig. 148.



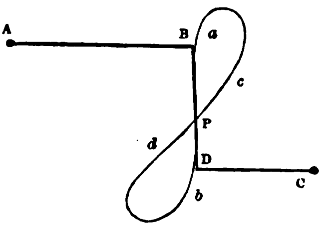
A B is the working beam of the engine, P Q the piston rod or pump rod attached at P to the rod B D, which connects A B and another bar, C D, moveable about a centre at C.

'When the working beam is put in motion the point B describes an arc on the centre A, and the point D describes an arc on the centre C, and the convexities of these arcs, lying in opposite directions, compensate for each other's variation from a straight line, so that the joint P, at the top of the piston rod, or pump rod, which lies between these convexities, ascends and descends in a perpendicular or straight line.'

116. This invention being clearly an example of aggregate motion, we proceed now to discuss it in a careful manner, and to examine its peculiar features.

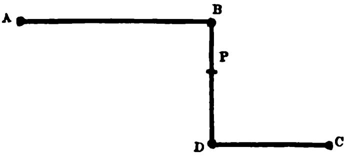
The lines A B and C D in Figure 149 are supposed to represent two rods moveable about centres at A and C, and connected by a link, B D. If B D be moved into every position which it can assume, the path of any point P in B D will be a sort of figure of eight, of which two portions, *a b*, *c d*, are nearly straight lines.

Fig. 149.



117. At the beginning of the motion let the rods be so placed that the angles at B and D shall be right angles. (Fig. 150.)

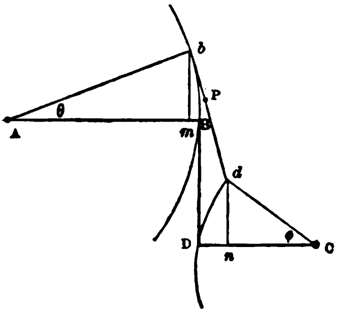
Fig. 150.



We shall now endeavour to discover that point in B D which most nearly describes a straight line, and in doing so, we first remark that B D begins to shift in the direction of its length, and therefore that the straight line in question coincides with B D.

Suppose the rods to be moved from the position A B D C into the position A *b d* C. (Fig. 151.) Draw *b m*, *d n* $\perp^{r}$ to A B and C D respectively, and let P be the required point; also let

Fig. 151.



$AB = r \quad bP = x \quad BAb = \theta$

$CD = s \quad PD = y \quad DCd = \phi$

We shall further suppose that the motion of A B and C D is restricted within narrow limits, and shall deal approximately with our equations, by putting

$$\sin\frac{\theta}{2} = \frac{\theta}{2} \quad \text{and} \sin\frac{\phi}{2} = \frac{\phi}{2}$$

$$\text{then } \frac{x}{y} = \frac{b\,\text{P}}{d\,\text{P}} = \frac{\text{B}\,m}{\text{D}\,n} = \frac{r(1 - \cos\theta)}{s(1 - \cos\phi)}$$

$$= \frac{r\,2\sin^2\frac{\theta}{2}}{s\,2\sin^2\frac{\phi}{2}}$$

$$= \frac{r\,\theta^2}{s\,\phi^2} \text{ nearly.}$$

But the link only turns through a very small angle, which may be considered to be nothing as a first approximation, in which case the vertical motion of B is equal to that of D,

$$\text{or} \quad b\,m = d\,n$$

$$r\sin\theta = s\sin\phi$$

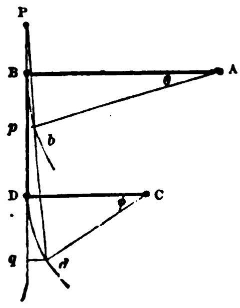
$$\text{whence } r\,\theta = s\,\phi \text{ nearly.}$$

$$\therefore \frac{x}{y} = \frac{r}{s} \times \frac{s^2}{r^2} = \frac{s}{r}$$

$$\text{or } \frac{b\,\text{P}}{\text{P}\,d} = \frac{\text{C D}}{\text{A B}}$$

i.e. the point P divides B D into two parts which are inversely as the lengths of the nearest radius rods.

Fig. 152.



118. If the radius rods be arranged on the same side of the link, the point P will lie in D B produced. (Fig. 152.)

Suppose the rods to be moved into the position A b d C, and draw $b\,p$, $d\,q$ $\perp^{r}$ B D and B D produced respectively.

$$\text{Then } \frac{b\,\text{P}}{d\,\text{P}} = \frac{b\,p}{d\,q} = \frac{r(1 - \cos\theta)}{s(1 - \cos\varphi)}$$

$$= \frac{r\,\theta^2}{s\,\varphi^2}$$

Also $r\theta = s\phi$ as before,

$$\therefore \frac{b\,\text{P}}{d\,\text{P}} = \frac{r}{s} \times \frac{s^2}{r^2} = \frac{s}{r}$$

a result which determines the position of P.

119. We have supposed that $\sin\theta = \theta$ and $\sin\phi = \phi$ in the previous investigation, and have examined the motion of that point in the connecting link which most nearly describes a straight line. We shall now inquire how much P really deviates from the rectilinear path at any given period of its motion.

In practice, the beam of an engine seldom swings through an angle of more than 20° on each side of the horizontal line, and within that limit the error consequent upon our assumption that the sine of an angle is equal to its circular measure would not be considerable; for we find, upon referring to the tables, that the circular measures of angles of 1, 5, 10, 15, 20 degrees, and the natural sines of the same angles are the following :—

Angle.	Circular Meas.	Natural Sine.	Difference.
1°	·0174533	·0174524	·0000009
5°	·0872665	·0871557	·0000108
10°	·1745329	·1736482	·0008847
15°	·2617994	·2588190	·0029804
20°	·3490659	·3420201	·0070458

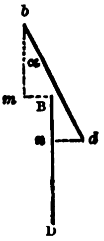
In an engine of the usual construction A B is equal to C D, and we shall simplify our results by making this supposition.

Let B D move into the position $b\,d$, and turn through an angle, α; it is very apparent that within the limits to which the rods move in practice, α will be much less than θ or ϕ,

so that we may regard α as a close approximation to the actual values of $\sin \alpha$ even when we do not adopt the same supposition with regard to θ and ϕ. (Fig. 153.)

The object of the investigation will be to determine ϕ in terms of θ, and we shall see that the deviation sought for depends upon the difference of the cosines of ϕ and θ.

Fig. 153.



As before, observing that $s = r$, we have

$$\text{B}\, m = r\,(1 - \cos\theta)$$
$$m\, b = r \sin\theta$$
$$d\, n = r\,(1 - \cos\phi)$$
$$\text{D}\, n = r \sin\phi$$

Let $\text{BD} = l$, then $l + m\,b = l \cos\alpha + \text{D}\,n$

$$\text{or } l + r\sin\theta = l\cos\alpha + r\sin\phi$$
$$\therefore\ r\sin\phi = r\sin\theta + l\,(1 - \cos\alpha) \quad (1)$$

Now α being the angle through which BD is twisted, and being moreover very small, we shall have

$$\begin{aligned} l\,\alpha &= \text{B}\,m + d\,n \text{ very nearly} \\ &= r\,(1 - \cos\theta) + r\,(1 - \cos\phi) \\ &= 2\,r\,(1 - \cos\theta), \text{ since } \phi \text{ is nearly equal to } \theta \end{aligned}$$
$$\therefore\ \alpha = \frac{2\,r}{l}(1 - \cos\theta) \text{ very approximately.}$$

By substituting in equation (1) we can calculate ϕ with considerable accuracy, and then the deviation of P from the vertical line will

$$= \frac{d\,n - \text{B}\,m}{2}$$
$$= \frac{r}{2}(\cos\theta - \cos\phi)$$

and can therefore be ascertained.

Ex. Let $\theta = 20$, and assume $r = s = 50$ inches, $l = 30$ in.

$$\begin{aligned} \therefore\ \alpha &= \frac{2\,r}{l}(\cdot 0603074) \\ &= \frac{10}{3}(\cdot 0603074) \\ &= \cdot 2010247 \end{aligned}$$

or α represents the angle of 11° 31′.

Substituting in equation (1) we have

$$\sin\phi = \sin 20 + \frac{3}{4}(1 - \cos 11^\circ\, 31')$$
$$= \cdot 3420201 + \frac{3}{5}(\cdot 0201333)$$
$$= \cdot 3541001$$
$$\therefore\ \phi = 20^\circ\, 44' \text{ nearly.}$$

Hence the deviation of P from the vertical

$$= \frac{50}{2}(\cos 20^\circ - \cos 20^\circ\, 44')$$
$$= 25\,(\cdot 0044544)$$
$$= \tfrac{1}{18}\text{th of an inch approximately.}$$

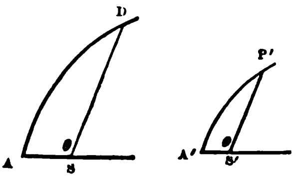
It may be shown that this amount of deviation is again capable of reduction if we cause the centres of motion, A and C, to approach each other by shifting them horizontally through small spaces.

120. The point P, whose motion has been examined, is usually found at the end of the air-pump rod. We have now to obtain a second point, also describing a straight line, and suitable for attachment to the end of the piston rod.

A species of jointed parallelogram enables us to effect this object upon the following principle:—

Two curves are said to be similar when two radii can be drawn from two points similarly situated, such that if any two other radii be drawn equally inclined to the former, the four are proportional.

Fig. 154.



Ex. Thus all parabolas are similar curves, and all ellipses with the same eccentricity are similar curves.

Let A, A′, be the vertices, S, S′, the foci of two parabolas. (Fig. 154.)

Then S A, S′ A′ are two lines drawn from two points similarly situated.

Let S P, S′ P′ be radii inclined at the same $\angle\,\theta$ to S A, S′ A′ respectively.

$$\text{Then } SP = \frac{2\,SA}{1 + \cos\theta}$$

$$S'P' = \frac{2\,S'A'}{1 + \cos\theta}$$

$$\therefore\ \frac{SP}{S'P'} = \frac{SA}{S'A'}$$

whence the curves are similar.

Again, if S be the focus, C the centre of an ellipse,

$$\text{the eccentricity} = \frac{CS}{CA}$$

Suppose the curves to represent ellipses of eccentricity e and e' respectively.

$$\therefore\ SP = \frac{SA(1 + e)}{1 + e\cos\theta}$$

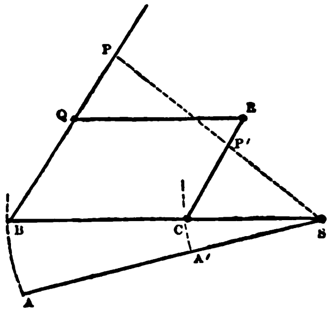
$$S'P' = \frac{S'A'(1 + e')}{1 + e'\cos\theta}$$

$$\text{Let } e = e'$$

$$\text{Then } \frac{SP}{S'P'} = \frac{SA}{S'A'}, \text{ or the curves are similar.}$$

121. The subjoined contrivance enables us to draw a curve similar to any given curve.

Fig. 155.



Let B Q R C represent a jointed parallelogram of which the sides B C, B Q are produced to convenient lengths; make any point S in B C S a centre of motion, and it will be found that by turning the frame round S, and at the same time opening or closing in some degree the angle Q B C, a point P in B Q produced may be made to follow the path of any given curve upon the plane of the paper. (Fig. 155.)

Join S P, cutting O R in P′, then the point P′ will trace out a curve similar to the path of P. For suppose B and C to have originally coincided with A and A′, so that S A′ A is a fixed line upon the paper.

$$\text{Then } \frac{\text{S P}}{\text{S P}'} = \frac{\text{S B}}{\text{S C}} = \frac{\text{S A}}{\text{S A}'}$$

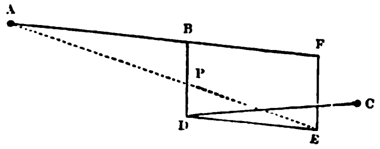
and the angle A S P = the angle A′ S P′

Therefore the points P and P′ trace out similar curves, and if one point describe a straight line, the other will do the same.

This arrangement, which is technically known as a *Pantograph*, enables us to complete the problem of the parallel motion.

122. To the system, A B C D, is superadded the parallelogram B F D E; A B F being the working beam of the engine. (Fig. 156.)

Fig. 156.



The point P is in the centre of B D, and is the point to which the air-pump rod is fixed; whereas the point E, which we are about to find, lies in A P produced, and is the point of attachment of the end of the piston rod.

$$\text{Let A B} = r,\ \text{C D} = s,\ \text{B F} = x,$$

$$\text{Then } \frac{x}{r} = \frac{\text{D P}}{\text{P B}} \text{ by similar } \triangle^{s}\ \text{A B P, D P E}$$

$$\text{But } \frac{\text{D P}}{\text{P B}} = \frac{\text{A B}}{\text{C D}} = \frac{r}{s} \therefore \frac{x}{r} = \frac{r}{s} \text{ or } x = \frac{r^2}{s}$$

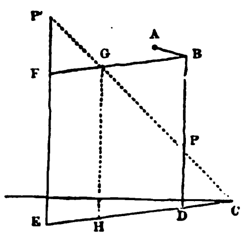
which equation determines the proportion between A B, C D, and B F, in order that the second point sought for may lie at the vertex, E, of the parallelogram.

123. Where a beam engine is used in a steam vessel the

beam must be kept as low down as possible, and the motion is altered as in the figure, but it is precisely the same in principle.

Let $AB = r$, $CD = s$, $DE = c$, $BD = l$, $FP' = x$, where P' is the point whose path is similar to that of P, being, in fact, the point to which the end of the piston rod is attached, and CDE is the beam of the engine. Draw $GH \parallel$ to FE. (Fig. 157.)

Fig. 157.



Then $\dfrac{HD}{CD} = \dfrac{GB}{CD} = \dfrac{BP}{PD}$

But $\dfrac{BP}{PD} = \dfrac{CD}{AB}$

$= \dfrac{s}{r}$

$\therefore \dfrac{HD}{s} = \dfrac{s}{r}$ or $HD = \dfrac{s^2}{r}$

Also $\dfrac{FP'}{FE} = \dfrac{FP'}{HG} = \dfrac{EH}{CH}$

$$\therefore \frac{x}{l} = \frac{DE - HD}{HD + CD} = \frac{c - \dfrac{s^2}{r}}{\dfrac{s^2}{r} + s} = \frac{rc - s^2}{s(r + s)}$$

$$\therefore x = \frac{l}{s} \cdot \frac{rc - s^2}{r + s} \text{ which gives } x.$$

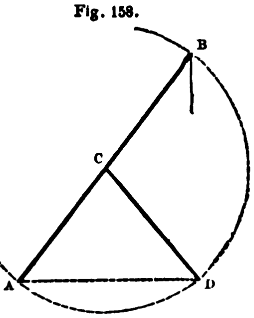
124. Another form of parallel motion was devised for marine engines before the principle of direct action was so generally adopted. It was fitted to the engines of the 'Gorgon' by Mr. Seaward, and has since been applied to small stationary engines.

It is remarkable as illustrating a mechanical principle for reducing friction upon an axis, by causing the driving pressure and the resistance to be overcome to act upon the same side of the centre of motion; for here the connecting and piston rods are both attached to the rocking beam upon the same side of its axis.

It is a modification of a simple geometrical fact.

Let the rod A B (Fig. 158) be bisected in C, and jointed at that point to another rod, C D, which is equal in length to A C. Suppose the point D to be fixed, and that the end, A, of the rod A B describes a straight line pointing to D, then B will also describe a straight line pointing to D.

Fig. 158.

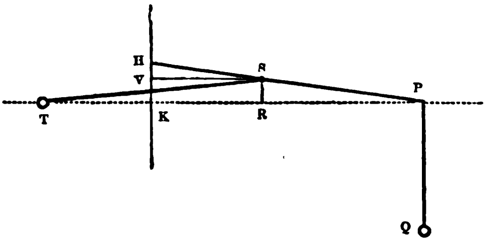


This is evident from the fact that C is always in the centre of a circle passing through A, D, and B, and of which A C B is the diameter.

The system of rods T S, H P, P Q, exhibits the parallel motion of the 'Gorgon' engines.

T and Q (Fig. 159) are the centres of motion, and H is the point which most nearly describes a straight line H K;

Fig. 159.



draw S R, S V, $\perp^r$ to T P and H K respectively.

Let T S $= a$, S H $= b$, S P $= c$, S T R $= \theta$, S P R $= \phi$.

$$\text{Then T R} = a \cos\theta = a\left(1 - 2\ \sin^2\frac{\theta}{2}\right)$$

$$= a\left(1 - \frac{\theta^2}{2}\right) \text{ nearly,}$$

$$\text{S V} = b\cos\phi = b\left(1 = \frac{\phi^2}{2}\right) \text{ nearly,}$$

$$\therefore \text{T K} = a - b - \frac{a\,\theta^2}{2} + \frac{b\,\phi^2}{2}$$

But the point H describes the straight line H K,

$$\therefore \text{T K} = a - b$$

$$\text{whence we have } \frac{b\phi^2}{2} - \frac{a\theta^2}{2} = 0$$

$$\text{or } a\,\theta^2 = b\phi^2$$

$$\text{But } \frac{a}{c} = \frac{\sin\phi}{\sin\theta} = \frac{\phi}{\theta} \text{ nearly,}$$

$$\therefore \frac{a}{b} = \frac{a^2}{c^2}$$

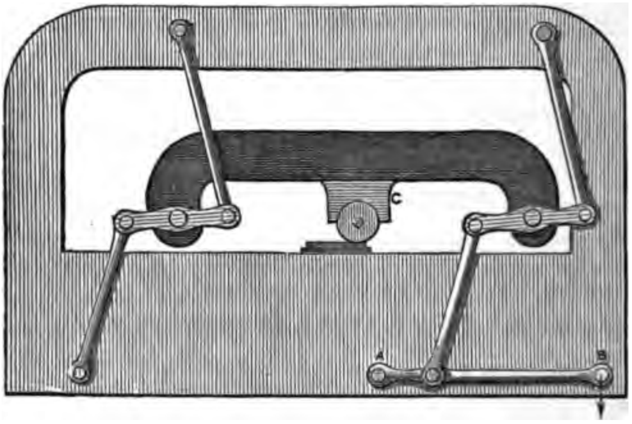
$$\therefore c^2 = ab,$$

or T S : S P :: S P : S H, a condition which must be fulfilled by the rods giving the parallel motion.

125. A *Parallel Motion* may also be useful in miscellaneous machinery.

In the old process of multiplying engraved steel plates at

Fig. 160.



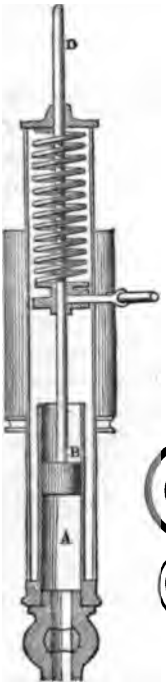
the Bank of England, which was practised before the art of electrotyping was understood, it was necessary to roll a hardened steel roller upon a flat plate of soft steel with a very heavy pressure, and so to engrave the plate. The difficulty of maintaining this pressure during the motion of

the roller upon the surface was overcome by the aid of the parallel motion indicated in Figure 160.

The system of jointed bars allowed the heavy frame C to traverse laterally, while the necessary pressure was obtained by a pull upon the end B of the lever A B, which lever was moveable round A as a centre of motion, and was further connected at B with some source of power.

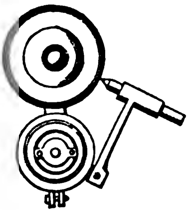
126. ***Watt's Indicator*** is an instrument used to ascertain the actual horse-power of a working steam-engine. The principle upon which it is constructed is the following:—

Fig. 161.



A pencil oscillates through the space of a few inches in a straight line, with a velocity which always bears a fixed ratio to that of the piston, and at the same time is the subject of a second motion at right angles to the former, which occurs whenever the pressure of the steam upon one and the same side of the piston becomes greater or less than that of the atmosphere.

Under the influence of these independent motions the aggregate path of the pencil will be a curve which is capable of interpretation, and which affords a wonderful insight into the working of the engine.



The indicator consists of a small cylinder, A, fitted with a steam-tight piston, B; the piston rod, B D, is attached to a spiral steel spring, which is capable of extension and compression within definite limits, and is enclosed in the upper part of a tube which carries the cylinder A.

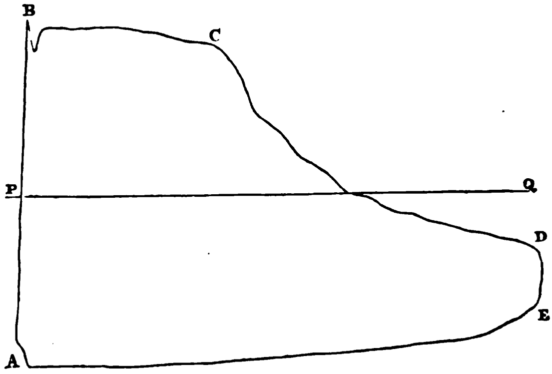
The pencil is attached to a point in the rod B D (Fig. 161),

and traces the indicator diagram upon a piece of paper wrapped round a second cylinder by the side of the first.

The cylinder, A, is freely open to the atmosphere at the top, and a stopcock admits the steam when required. The indicator is usually fixed upon the cover at one end of the steam cylinder of the engine. When the stopcock is opened and the lower side of B is in free communication with the interior of the cylinder, the pressure of the steam will be usually greater or less than that of the atmosphere; if it be greater, B will rise against the pressure of the spring, and if it be less, the pressure of the atmosphere upon the upper surface of B will overcome the resistance of the spring and cause the pencil to descend.

At the same time, the cylinder which carries the paper is made to turn with a motion derived at once from that of the piston in the engine, but much less in degree, and thus a curve is traced out somewhat of the character represented in Fig. 162.

Fig. 162.



Here P Q is the atmospheric line, and is the path of the pencil when the pressure of the steam is equal to that of the atmosphere, or when the spiral spring is neither extended nor compressed.

As the steam enters the cylinder, the piston may be supposed to be descending, and the pencil to be describing the upper portion of the curve; when the piston returns, the pencil moves to the left through D E A, and thus the diagram is traced out. We may examine this matter with more particularity as follows: the steam is admitted just before the piston reaches the top of its stroke by giving a small amount of lead to the slide valve, and the pencil rises at once with a rapid motion from A to B; the full pressure of the steam is then maintained while the pencil, recording a portion of the travel of the piston, moves from B to C; at C the steam is cut off, and the pencil falls gradually as the steam expands with a diminishing pressure; at D the steam pours into the condenser, and the fall becomes sudden; from E to A the cylinder is in full communication with the condenser, and the pencil describes a line somewhat inclined to the line P Q, the position and form of which depends upon the perfection of the vacuum in the condenser.

The strength of the spiral spring being ascertained, the curve tells us exactly the number of pounds by which the pressure of the steam urges the piston onward during every inch of its path in one direction, and the amount of resistance which the uncondensed vapour or gases existing in the condenser oppose to its passage in the other direction; the area of the curve, therefore, affords an estimate of the work done in the engine during one complete stroke, and is a graphic representation of the same; the engineer estimates this area by simple measurement in the most direct manner which occurs to him, and then the actual indicated horse-power is obtained by multiplying the work done in one stroke by the number of strokes in a minute, and then dividing by 33,000, the number of pounds that a horse can raise through one foot in one minute.

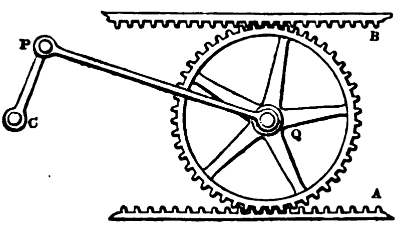
127. In some printing machines the table is driven by a

crank and connecting rod, and the length of its path may be doubled upon the principle under discussion.

A wheel rolling upon a plane is a case of aggregate motion; the centre of the wheel moves parallel to the plane, the wheel itself revolves about its centre, and these two simple motions give the aggregate result of rolling.

Let a wheel, Q (Fig. 163), be attached to the end of the connecting rod P Q, so that it can turn freely on its centre, Q.

Fig. 163.



Let the wheel revolve between two racks, A and B, whereof A is fixed to the framework of the machine, and B is attached to the table.

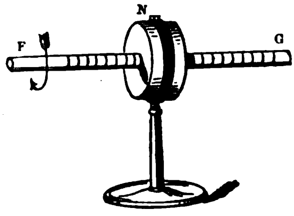
The rack B receives the motion of Q in its twofold character, and moves through exactly twice the space that it would describe if connected simply with the point Q.

The size of the wheel makes no difference in the result.

In the same way, if a beam of timber be moved longitudinally upon friction rollers, the travel of the beam will be twice as great as that of the rollers.

128. A further illustration of aggregate motion occurs in machinery for drilling and boring.

Fig. 164.



In a drilling machine the spindle which carries the cutting tool revolves rapidly, and at the same time advances slowly in the direction of its length.

The movement is obtained upon a very obvious principle.

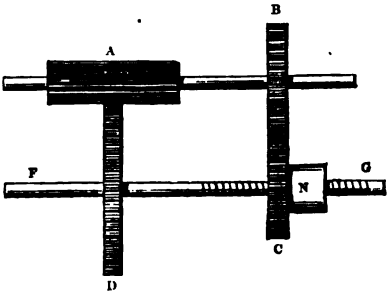
Conceive a nut, N (Fig. 164), to be placed upon a screw-bolt, F G, and to be so held in a

ring or collar that it can rotate freely without being capable of any other motion.

If the nut be fixed, and F G be turned in the direction of the arrow, it is clear that the bolt must advance through the nut; if, again, the screw be prevented from turning, and the nut be made to rotate in the same direction as before, the bolt will come back again. And, finally, if by any contrivance different amounts of rotation be impressed at the same time upon the nut and the screw, the bolt will receive the two longitudinal movements simultaneously, and the aggregate motion will be the sum or difference of its component parts.

129. Suppose the wheels D and C to be attached to the bolt and nut respectively, and to be driven by the pinions A and B, and let A, B, C, D represent the numbers of teeth upon the respective wheels. (Fig. 165.)

Fig. 165.



If (a) be the number of rotations made by A or B during (m) rotations of C and (n) of D, we have $\frac{m}{a} = \frac{B}{C}$ $\frac{n}{a} = \frac{A}{D}$

Therefore (a) rotations of A will cause a travel of the bolt F G through $(m - n) \times$ pitch of the screw

$$= a\left(\frac{B}{C} - \frac{A}{D}\right) \times \text{pitch of the screw.}$$

130. We shall first of all examine the construction of a small *Drilling Machine*, which can be worked either by hand or steam-power, and which is not self-acting.

The drill spindle, with a screw thread formed upon the upper part of it, is sketched in Fig. 166: a longitudinal

slot or groove, *m n*, is cut in the lower portion of the drill spindle, and a corresponding projection or feather is attached to the inside of the pipe, A B, and works in the groove, by

Fig. 166.

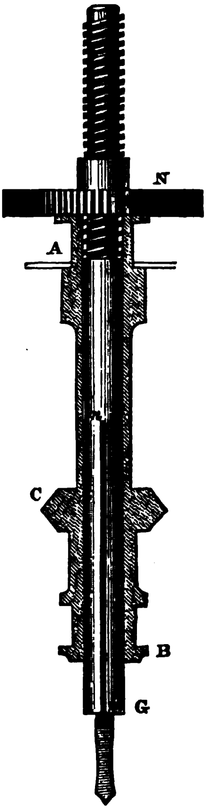
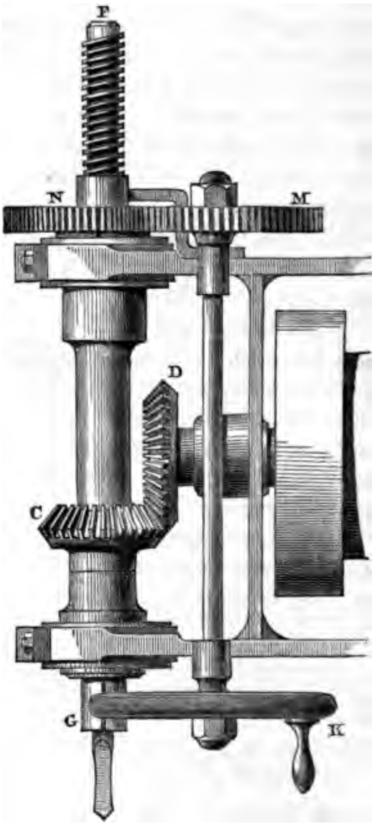


Fig. 167.



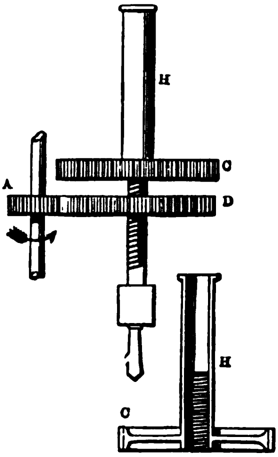
which construction it is provided that the spindle shall be moveable along the tube, and yet be made to rotate with it *in every* position.

The general arrangement of the machine is shown in Figure 167; the power is applied to turn the bevil wheel D, and thus to cause the rotation of A B: the handle K actuates the wheels M and N, whereof the latter is a nut fitted upon the screwed part of the spindle.

As the cutting proceeds, the workman slowly depresses the drill spindle by turning the handle; he can do this without at all interfering with the rotation of the cutter, and if the machine were self-acting it would be the object of some special contrivance to produce a corresponding depression of the drill by imparting a slow and uniform longitudinal movement to the spindle.

131. A Drilling Machine by Mr. Bodmer, of Manchester, is made self-acting in the following manner:—

Fig. 168.



The drill spindle (Fig. 168) has a screw thread traced upon it; a groove is cut longitudinally along the spindle, and a projection upon the interior of the boss of the wheel D fits acccurately into the groove.

Thus the spindle can traverse through the wheel D, although the spindle and wheel must turn together.

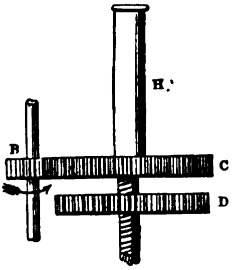
A nut, H, in the form of a pipe, and having a wheel, C, at the bottom of it, receives the spindle; this wheel and pipe are shown separately in section.

If a pinion, A, turning in the direction shown by the arrow, engage the wheel D, it will screw the spindle rapidly through the nut H, and bring it down towards the work.

Suppose a second pinion B (Fig. 169) turning in the same direction as A to act upon C, it will move the nut instead of the screw, and the drill spindle will rise rapidly.

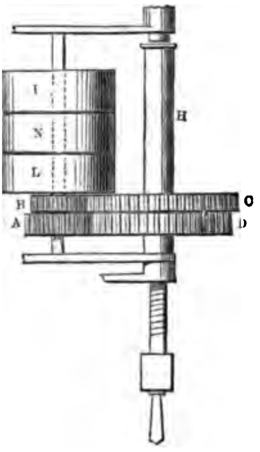
Thus far we have provided for bringing the spindle down to its work, and for raising it up again; it remains to apply the principle of aggregate motion, to cause the drill spindle to become the recipient of these two movements in a nearly equal degree, and thereby to ensure the slow descent accompanied by a rapid rotation, which is required in process of drilling.

Fig. 169.



The result of the combination is shown in the next diagram, where the wheels A and B are moved together; the wheel A tends to depress the spindle, the wheel B tends to raise it, and the spindle descends by the difference of these two motions having further the motion of rotation given by the wheel A. (Fig. 170.)

Fig. 170.



The motions of A and B are obtained from the driving pulleys I, N, and L.

I is an idle pulley; N drives A and L drives B. When the strap is on N the drill descends to the work; when the strap is on L it ascends from the work, and when the strap is partly on N and partly on L the drilling proceeds.

132. Mr. Whitworth's Friction Drilling Machine is an elegant application of the principle under discussion.

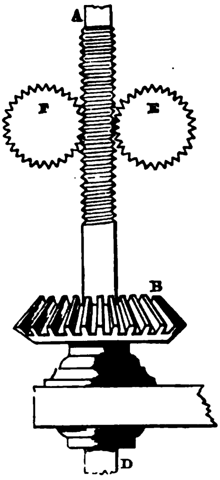
A D is the drill spindle, driven in the usual manner by the bevil wheel B. (Fig. 171.)

E and F are two worm wheels embracing the screwed portion of the spindle upon opposite sides.

If E and F be prevented from turning, they will

form a nut through which the spindle will screw itself rapidly.

Fig. 171.



If E and F be allowed to turn quite freely, the drill spindle will set them in motion, and the nut will be virtually eliminated. The drill spindle may then be regarded as the recipient of two equal and opposite motions; it is depressed by screwing through a nut, it is elevated by the turning of the wheels.

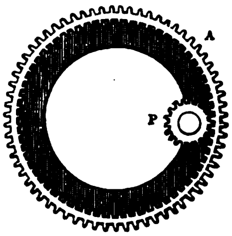
If the rotation of the wheels be in any degree checked by the application of friction, the equality is destroyed, and the drill spindle descends to a corresponding extent.

A friction brake, regulated by a screw, restrains the motion of E and F, and gives a perfect command over the working of the machine.

When B is at rest the worm wheels act upon the spindle as a pinion does upon a rack, and the drill can be rapidly brought down to the work.

133. A *Boring Machine* would be employed to give an accurately cylindrical form to the interior surface of a steam cylinder.

Fig. 172.



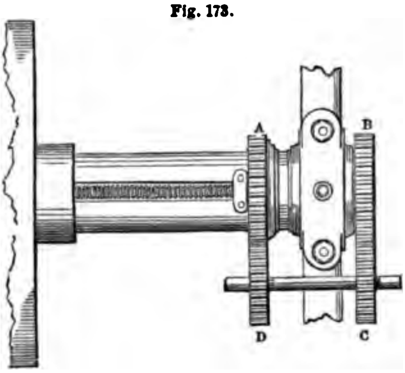
In the annexed example the boring cutters are attached to a frame which rides upon a massive cast-iron shaft or boring bar, and rotates with it; this frame is further the recipient of a slow longitudinal movement given by a screw. (Fig. 172.)

An annular wheel, A, shaped as in the figure, rides loose upon the bar, and drives a pinion, P, at the end of the feeding screw which advances the cutters,

the boring bar being recessed in order to receive the screw.

It is quite apparent that as long as the rotation of the wheel A is identical with that of the boring bar, the pinion P will not turn at all; and further, that a slow motion will be impressed upon P, if the rotation of A is made to lag a little behind that of the bar.

Fig. 173.



A wheel, B, is keyed to the bar, and a small shaft at the side carries the wheels C and D, and thus motion is imparted to A, and thence to the feeding screw. Let the numbers of teeth upon B, C, D be 64, 36, 35, and let the wheel A have 64 teeth, both upon the outside and the inside of its circumference, the pitch of the screw being $\frac{1}{2}$ an inch, and the number of teeth upon the pinion being 16. (Fig. 173.) Here

$$e = \frac{B \times D}{C \times A}$$

$$= \frac{64 \times 35}{36 \times 64}$$

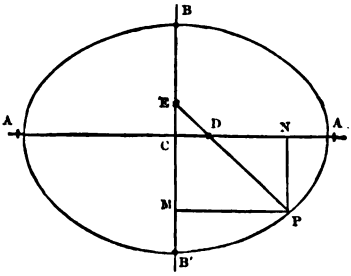
$$= \frac{35}{36}$$

i. e. A loses $\frac{1}{36}$th of a revolution for every complete rotation of the boring bar. At the same time the pinion P moves through $\frac{1}{36} \times \frac{64}{16}$ or $\frac{1}{9}$ of a revolution, and the cutter advances through $\frac{1}{9} \times \frac{1}{2}$ an inch or through $\frac{1}{18}$th of an inch.

134. The *oval chuck* affords another example of aggregate motion. It is based upon the following property of an ellipse.

Let A C A$'$, B C B$'$ (Fig. 174), represent two grooves at right angles to each other, and traced upon a plane surface; P D E, a rod furnished with pins at D and E: if this rod be moved into every possible position which it can assume while the pins remain in the groove, the point P will describe an ellipse.

Fig. 174.



Draw P N $\perp^r$ to A C, and P M $\perp^r$ to C B

Let $\text{C N} = x, \quad \text{P E} = a$

$\text{P N} = y, \quad \text{P D} = b$

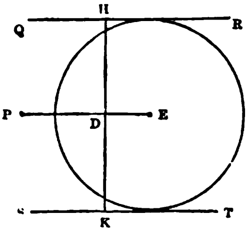
$$\text{Then } \frac{x}{a} = \frac{\text{P M}}{\text{P E}} \quad \frac{y}{b} = \frac{\text{P N}}{\text{P D}} = \frac{\text{E M}}{\text{P E}}$$

$$\therefore \frac{x^2}{a^2} + \frac{y^2}{b^2} = \frac{\text{P M}^2 + \text{E M}^2}{\text{P E}^2} = 1$$

which is the equation to an ellipse.

135. In drawing an ellipse we should fix the paper and move the rod over it, but in turning an ellipse in a lathe we should fix the describing tool and move the piece of wood or metal underneath it; thus the conditions of the problem become changed, and the construction is modified accordingly.

Fig. 175.



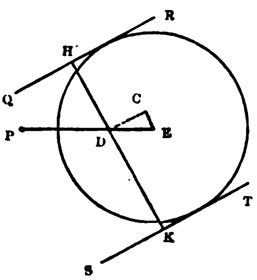
An equivalent for the grooves A C A$'$, B C B$'$ may be found as follows:

Describe a circle about E of radius larger than E D (Fig. 175), and let two parallel bars, Q R, S T, be connected

by a perpendicular link H K equal in length to the diameter of the circle, and thus form a rigid frame embracing the circle, and capable of moving round it.

As the frame moves round the circle let H K pass through D in every position as represented in Fig. 176, draw D C parallel to Q R, and E C parallel to H K, then it is not difficult to understand that the triangle D C E in Fig. 176, is exactly the same as the triangle D C E in Fig. 174; and that as we formerly moved the bar E P over a plane and described an ellipse, so now we have the same motion with a fixed bar and a moveable plane, and obtain precisely the same curve.

Fig. 176.



This is a very good example of aggregate motion. The plane upon which the ellipse is traced is the subject of two simultaneous movements; a line, H K, in the plane is made to revolve by the one round D as a centre, and by the other the same line receives a sliding motion in alternate directions through D.

Thus an oval, or more properly an ellipse, may be turned in the lathe.

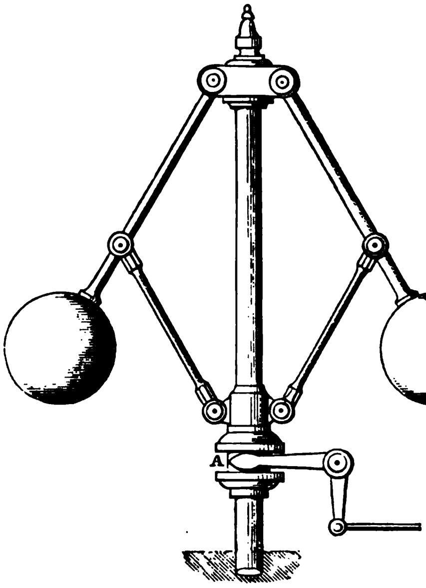
136. The *Governor* of a steam-engine usually appears under the form invented by Watt, and has proved of the greatest possible value in steam machinery.

The annexed diagram (Fig. 177) shows the construction of this appendage to an engine, and the principle of its action is briefly the following:—

The engine imparts rotation to the balls of a heavy conical pendulum, and maintains them at a certain inclination to the vertical; if the velocity of the engine be increased, the balls open out more widely; if it be diminished, they collapse, and in doing so they move the end, A, of a system of levers

which is connected with a throttle valve, and thereby regulate the supply of steam to the cylinder.

Fig. 177.



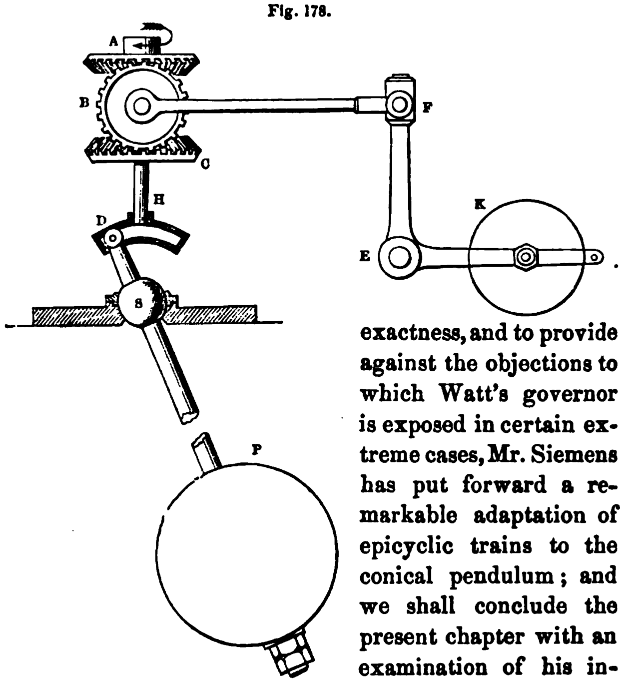
An engineer can easily arrange that the variation in speed admitted by the governor shall not exceed one-tenth of the mean velocity, but it is of the essence of the invention that some change in the speed should be admissible: the balls cannot alter their position unless the time of a revolution changes, and they cannot accumulate such additional momentum as may be sufficient to move the valve until the rate of the engine has sensibly altered.

In some cases, as where the engine drives machinery for very fine spinning, it may be desirable to obtain an almost absolute uniformity of motion; or, again, it may be an object

to avoid the fluctuations in speed to which the common governor is liable when any sudden change occurs in the load upon the engine.

In order to control the engine with almost theoretical

Fig. 178.



exactness, and to provide against the objections to which Watt's governor is exposed in certain extreme cases, Mr. Siemens has put forward a remarkable adaptation of epicyclic trains to the conical pendulum; and we shall conclude the present chapter with an examination of his invention.

The original construction of this governor is exhibited in the diagram (Fig. 178), and is better suited to the purpose of explanation than a more recent arrangement.

An epicyclic train of three equal wheels, A, B, C, imparts motion to the conical pendulum; of these, A is driven by the engine, and B is capable of running round A and C to a small extent defined by stops, the joints at F and B being so constructed as to permit of such a motion.

The wheel B is also connected by the system of levers to a weight, K, and shuts the steam valve when its motion has lifted K through a certain space.

The valve spindle passes through the centre of motion, E, and is turned by the arm F E.

A conical pendulum, D P, is suspended by a ball-and-socket joint at S, and the extremity D moves in a circular groove, D H.

A certain amount of maintaining force is absorbed in preserving this pendulum at a constant angle with the vertical, and it is a part of the contrivance to increase artificially the friction which opposes the motion of the pendulum, and thus finally to make the pressure exerted by the weight, K, an actual measure of the amount of such maintaining force.

The governor is at work when the velocity of the engine suffices to keep K raised through a small space.

In order to understand the peculiar action introduced by the epicyclic train, we should remember that one of these two things will happen: either A and C will turn at the same rate, or else B will shift its position and run round the axis A H; there can be no departure from the rigid exactness of this statement.

Now the wheel C is connected with the pendulum, and its rotation cannot be maintained without a constant expenditure of force; in other words, the tendency of C is to lag behind A, and to cause B to run round the axis A H.

This indisposition in C to accept the full velocity of A is artificially increased by the friction until B shifts its position and raises the weight K permanently, and then of course it follows that the pull of K evidences itself as a constant pressure tending to drive the wheel C.

The pendulum being in this manner retained in permanent rotation, suppose that any increase were to occur in the velocity of A, the wheel C is in connection with a heavy revolving body, and can only change its velocity gradually,

but K is already lifted, in the sense of being counterpoised, and the smallest increase of lifting power can therefore raise it higher; thus the tendency to an increase in the velocity of A will at once cause B to change its position, and will control the steam valve.

So sensitive is this form of governor to fluctuations in speed, that an alteration of $\frac{1}{60}$th of a revolution may suffice to close the throttle valve altogether. The power to move the valve spindle is also very great, and offers a remarkable contrast to that exerted in other arrangements.

In the method now adopted at Greenwich for registering the times of transits of the stars by completing a galvanic circuit at the instant of observation, a drum carrying a sheet of paper is made to revolve once in two minutes. A pricker actuated by an electro-magnet, and moving slowly in a lateral direction, is set in motion at the end of each beat of the seconds' pendulum of a clock, and thereby makes a succession of punctures in a spiral thread running round the drum. The observer touches a spring at the estimated instant of the time of transit of a star across a wire of the telescope, and producing a puncture intermediate to those caused by the pendulum, does in fact record the exact period of the observation. The regularity of motion in the drum is a matter of vital importance, and is ensured by the employment of a clock train moving under the control of this pendulum of Mr. Siemens.

CHAPTER VI.

MISCELLANEOUS CONTRIVANCES.

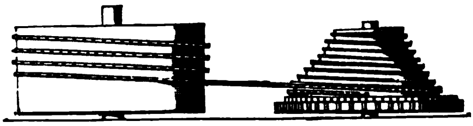
We propose to examine in our concluding chapter various miscellaneous pieces of mechanism, and certain special contrivances which are of frequent occurrence in machinery, and with which a student of applied mechanics ought to render himself familiar.

137. *The Fusee* is adopted in chronometers, and in most English watches, in order to maintain a uniform force upon the train of wheels, and to compensate for the decreasing power of the spring.

The spring is enclosed in a cylindrical barrel, and sets the wheels in motion by the aid of a chain wound partly upon the barrel and partly upon a sort of tapering drum called a fusee. (Fig. 179.)

As the spring uncoils in the barrel the pull of the chain decreases in intensity; at the same time, however, the chain

Fig. 179.



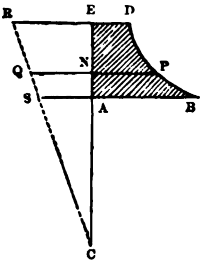
unwinds itself from the fusee, and continually exerts its strain at a greater distance from the axis, i.e. with a greater leverage, and with more effect.

The theoretical form of the fusee is an hyperbola.

138. To prove this statement we proceed as follows :—

Let D P B represent the generating curve of a fusee, E A being its axis. (Fig. 180.)

Fig. 180.



Draw D E, P N, B A perpendiculars on E A; take E R, Q N, S A to represent the pull of the spring when the chain is at D, P, and B respectively.

According to Hooke's Law, '*ut tensio sic vis*,' the force of the spring decreases uniformly, and ∴ R Q S is a straight line; produce it to meet E A in C, and let C N $= x$, N P $= y$. Now, in order that the fusee may accomplish its object, the product of the pull of the spring into the arm N P must remain constant for every position of P.

But the pull of the spring varies as Q N, or as C N, which is in a constant ratio to Q N, whence we infer that the product (P N × C N) is constant, or that $xy =$ a constant quantity, an equation which represents an hyperbola.

139. In mechanism the fusee is frequently employed to transmit motion instead of to equalise force, and enables the mechanic to derive a continually increasing or decreasing circular motion from the uniform continuous rotation of a driving shaft.

The groove of the fusee may be traced upon a cone or other tapering surface, or it may be compressed into a flat spiral curve: in all cases the effect produced will be that due to a succession of arms which radiate in perpendicular directions from a fixed axis, and continually increase or decrease in length.

The fusee can of course only make a limited number of turns in one direction.

140. A *Flat Spiral Fusee* occurs in spinning machinery, and serves to regulate the velocity of the spindles and to ensure the due winding of the thread in a succession of conical layers upon a bobbin or '*cop*.'

The formation of the *cop* is a problem upon which a vast amount of mechanical ingenuity has been expended; and, without entering too much into details, we may observe that there are two distinct stages in the process of winding the yarn upon a spindle so as to produce a finished cop.

Fig. 181.

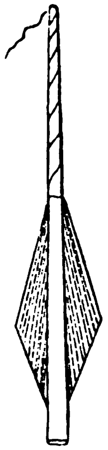
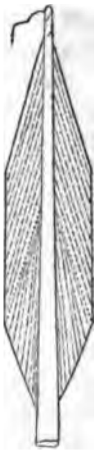


Fig. 182.

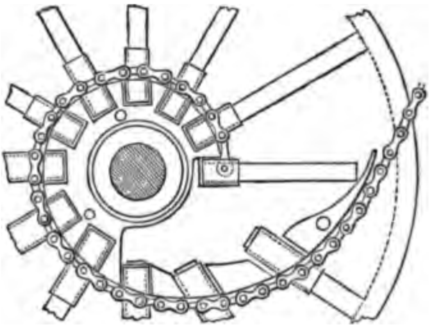


The *Copbottom* (Fig. 181) is first formed upon a bare spindle by superposing a series of conical layers with a continually increasing vertical angle.

The body of the cop is then built up by winding the yarn in a series of equal conical layers. (Fig. 182.)

The winding-on of the yarn begins at the base of the cone, and proceeds upwards to the vertex; the spindles are driven by a drum which rotates under the pull of a chain, and it is evident that they can be made to revolve with increasing rapidity by placing a fusee upon the driving shaft and causing the chain to coil upon it.

Fig. 183.



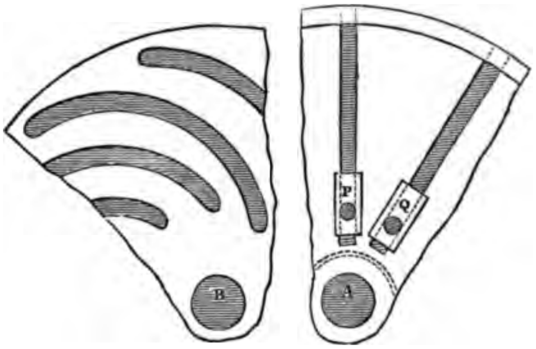
Such an arrangement, as shown in Fig. 183, will be adapted to the winding of a uniform supply of thread upon a conical surface; and we can easily comprehend that a fusee of fixed dimensions will do very well for building up the body of the cop after the foundation is made. The main difficulty occurs in producing the cop-

bottom, where the series of conical layers of continually increasing vertical angle demands a fusee whose dimensions shall gradually contract.

The method of contracting the form of the fusee may be explained as follows :—

Fig. 184 represents portions of two flat discs having axes at A and B, and upon which are cut radial and curved grooves in the manner indicated; it being arranged that when one plate is placed upon the other, the pins P and Q shall travel in both sets of grooves at the same time.

Fig. 184.



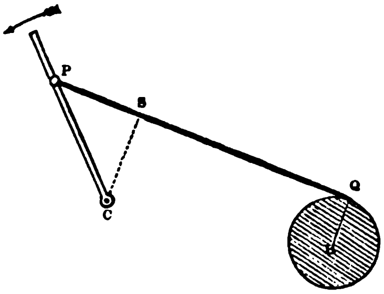
We can easily see that the blocks which carry the pins will move along the radial grooves as the disc B turns relatively to A, and that by this combination we can obtain a spiral fusee of any required form, and can contract or enlarge its dimensions at pleasure.

141. *Mr. Roberts's 'winding-on motion'* reposes upon the principle of the fusee, though in a modified form.

Let one end of a rope which is coiled round a drum be attached to a point, P, in the moveable arm C P: it is evident that the rotation of C P about the centre of motion C will cause some portion of the rope to be unwound from the barrel. (Fig. 185.)

Draw C S perpendicular to the direction of the rope; then, at any instant of the motion, the arrangement supplies the jointed rods, C P, B Q, mentioned in Art. 52, and it is manifest that the rate at which the string is unwound will vary as the perpendicular C S.

Fig. 185.

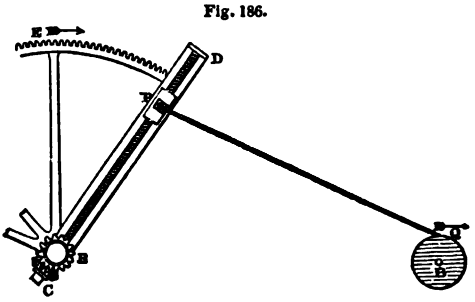


This rate is greatest when C P is perpendicular to P Q, but decreases to nothing when C S vanishes, and here, therefore, the varying arm of the fusee exists in a latent form.

Next conceive that the conditions are changed, and that the drum B moves to the right hand through a moderate space while C P remains fixed; the cord will unwind from the drum with a nearly uniform velocity.

If, finally, the arm C P be not fixed, but be made to move from a position a little to the left of the vertical into one nearly horizontal during one journey of the drum, it is abundantly clear that we shall subtract from the uniform

Fig. 186.



motion of unwinding that amount which is due to the action of a fusee, and that if the spindles derive their motion

from the rotation of the drum they will continually accelerate as the drum recedes from C P. In this way we can make up the body of the cop. To form the copbottom, it is necessary that the winding on should begin more rapidly, and should gradually diminish; this character of motion is produced by causing the nut P to traverse C D in successive steps during each journey of the drum. As soon as the cop has attained its full diameter, the nut ceases to travel along C D, and the thread is wound in uniform conical layers. (Fig. 186.)

142. If two cords be wound in opposite directions round a drum, A, and the ends of the cords be fastened to a moveable carriage, it is evident that the rotation of A in alternate directions will cause a reciprocating movement in the carriage. (Fig. 187.)

Fig. 187.

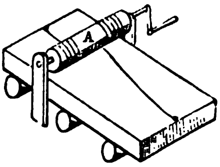
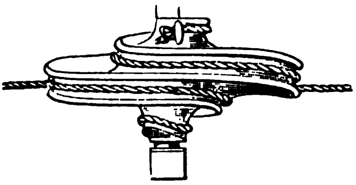


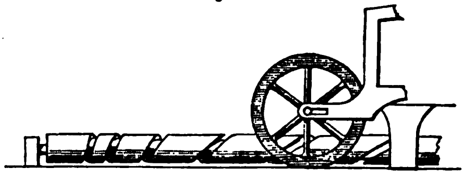
Fig. 188.



The drum A (Fig. 188) has been replaced by a spiral fusee in the self-acting mule of Mr. Roberts, and thus the motion of the carriage is gradually increased till it has reached the middle of its path, and then decreases to the end of the movement.

143. A helical screw of a varying pitch traced upon a

Fig. 189.

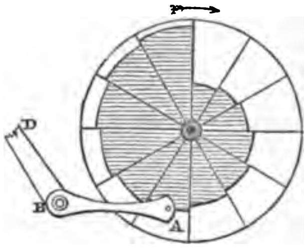


cylinder would produce a similar variable motion of the

mule-carriage, and has been applied in a machine constructed upon a different principle, in order to obtain a continually decreasing motion of the carriage. In effect it replaces the fusee. (Fig. 189.)

144. The *snail* is chiefly found in the striking part of repeating clocks. It is a species of fusee, and is used to define the amount of angular deviation of a bent lever A B D, furnished at the end A with a pin which is pressed against the curve of the snail by a spring, and attached at the other end to a curved rack, whose position determines the number of blows which will be struck by the hammer of the clock.

Fig. 190.



In order to form the snail, a circle is divided into a number of equal parts (twelve, for example), and a series of steps are formed by cutting away the plate and leaving a circular boundary in each position. (Fig. 190.)

As the snail revolves, A B D passes by jerks into twelve different positions, and the clock strikes the successive hours.

145. The *disc and roller* is equivalent to the fusee, and is now but little used, on account of the probability that the roller will occasionally slip.

This arrangement consists of a disc A (Fig. 191), revolving round an axis $\perp^r$ to its plane and giving motion to a rolling plate B, fixed upon an axis which intersects at right angles the axis of the disc A.

Supposing the rotation of the disc to be uniform, that of the roller B will continually decrease as it is shifted towards the centre of A, and conversely.

This is precisely the effect produced by a fusee.

The roller may be a wheel furnished with teeth, and may roll upon a spiral rack as shown in Fig. 192.

As the disc revolves, the pinion P slides upon the square shaft, and is kept upon the rack by the action of

Fig. 191.

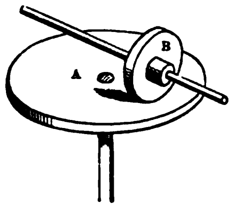
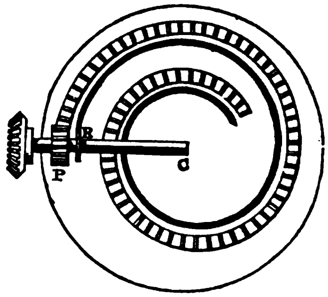


Fig. 192.

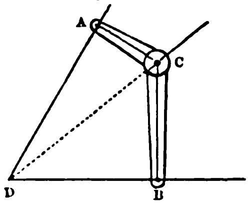


a guide-roller, R, which travels along the spiral shaded groove in the manner indicated in the diagram.

This example is by no means put forward as a good mechanical contrivance.

146. *Bell-crank Levers* serve to change the line of direction of some small motion, and are of universal application. They consist simply of two arms standing out from a fixed axis so as to form a bent lever.

Fig. 193.



1. Suppose it to be required to construct a bell-crank lever so as to change the direction of some small motion from the line B D into the line D A, where B D, A meet in a point D. (Fig. 193.)

Draw D C, dividing the angle at D into two parts whose sines are in the ratio of the velocities of the movements in the given directions.

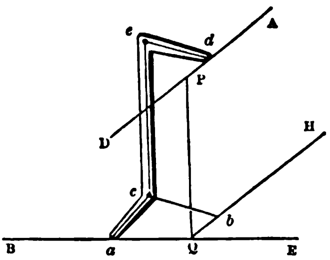
In D C take any convenient point C, and draw C A, C B, $\perp^r$ to D A and D B respectively, then A C B will be the bell-crank lever required.

It is evident that the velocities of A and B are directly as the arms C A, C B, i.e. in the ratio of sin. C D A to sin. C D B: also that the motion in D A or D B becomes more nearly rectilinear the farther we remove C from the point D.

Any play which may be necessary at the joints A and B, by reason that the ends of the levers really describe small circular arcs, may be easily provided for in the actual construction.

2. To change the direction from one line to another not intersecting it.

Fig. 194.



Draw P Q, a common perpendicular to the lines A D and B E (Fig. 194), through Q draw Q H parallel to D A; construct a bell-crank lever, *a c b*, for the movements as transferred to the lines B Q, Q H; draw *c e* parallel to P Q and equal to it, and further make *e d* parallel and equal to *c b*.

The piece *a c e d* will be the lever required.

An example of the use of a bell-crank lever of the second kind occurs in that portion of the rifling machine discussed in Art. 39, and by means of it the longitudinal movement of the rod R N is transferred from one horizontal line to another, also horizontal, but in a plane at right angles to the original direction.

147. In the transfer of motion from one axis to another, it often happens that we wish to deduce a rotation which may be made more or less rapid from one which is perfectly uniform.

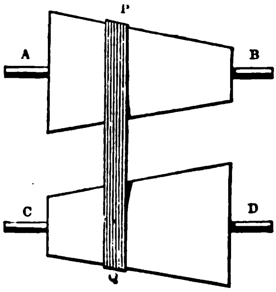
Conical Pulleys will give this result, and are represented in Fig. 195, where two cones moveable about the axes A B, C D, are connected by a driving band P Q.

The rotation of A B being uniform, it is at once evident

that the rotation of C D will continue to decrease as the strap is shifted from C towards D.

One of the cones is sometimes replaced by a cylindrical drum, in which case the strap must be kept stretched by a tightening pulley.

Fig. 195.



As an illustration, we refer to the use of these conical pulleys in the manufacture of stoneware jars, and other large earthenware vessels; where a mass of clay is fashioned into the required form upon a rotating table, and the workman varies the speed of the table according to the requirements of the work by shifting the driving strap along a pair of cones.

Speed Pulleys form one variety of conical pulleys, and are so called because they allow of the transfer of different velocities of rotation from one shaft to another; they are much used in engineers' factories.

They are made in a series of steps, and are connected by a band which may be either open or crossed.

There is a peculiarity when the band is crossed which does not exist otherwise, and we shall now show that the same band, when crossed, will be sure to suit every pair of pulleys which are connected by the simple relation that the sum of the radii of each opposite pair is equal to a constant quantity.

This gives a very easy rule for making the pulleys, and the proof is the following:—

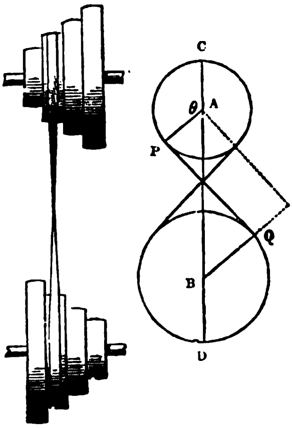
Let a pair of pulleys connected by a crossed strap be represented in Fig. 196, and let $AP = x$, $BQ = y$, $PAC = DBQ = \theta$,

Then $CPQD = x\theta + y\theta + PQ = (x + y)\theta + PQ$.

If now A P be increased by a given quantity, and B Q be diminished by the same quantity, P Q will remain con-

stant and parallel to itself; also θ will not change, and $x + y$ will not change, therefore C P Q D will be unaltered in length.

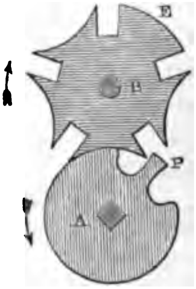
Fig. 196.



In practice, open bands are usually preferred to those which are crossed; the latter embrace a larger portion of the circumference, and are therefore less liable to slip, but they rub and wear away at the point where they cross. When an open band is used, the pulleys are so adjusted that the same band shall suit every pair in the series, but there is not the same easy method of obtaining the result.

148. Where a train of wheels is set in motion by a spring enclosed in a barrel, it becomes of consequence not to overwind the spring; the *Geneva stop* has been contrived with the view of preventing such an occurrence, and will be found in all watches which have not a fusee.

Fig. 197.



Here a disc A, furnished with one projecting tooth P, is fixed upon the axis of the barrel containing the mainspring, and is turned by the key of the watch. (Fig. 197.)

Another disc, B, shaped as in the drawing, is also fitted to the cover of the barrel, and is moved through a certain angle every time that the tooth P passes through one of its openings, being prevented from rotating at other times by the action of the convex surface of the disc A.

In this manner each rotation of A will advance B through a certain space, and the motion will continue until the

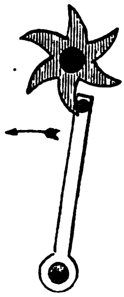
convex surface of A meets the convex portion E, which is allowed to remain upon the disc B in order to stop the winding-up.

The winding action having ceased, the discs will return to their normal positions as the mechanism runs down.

149. The *Star Wheel* is used in cotton-spinning machinery, and is analogous to the Geneva stop.

If the convex portion E were removed so as not to interfere with the rotation of A, we should virtually possess a star wheel in the disc B.

Fig. 198.



In that case each rotation of A would advance B by the space of one tooth, or we should convert a continuous circular motion into one of an intermittent character.

The usual form of the star wheel is given in Figure 198, where the revolving arm encounters and carries forward a tooth at each revolution.

It is as if a wheel with one tooth were to drive another with several teeth.

150. *The Double Eccentric for reversing an Engine.* When the piston is near the middle of its stroke in a locomotive or marine engine, the slide-valve will have moved over the steam-ports in the manner pointed out in Fig. 199.

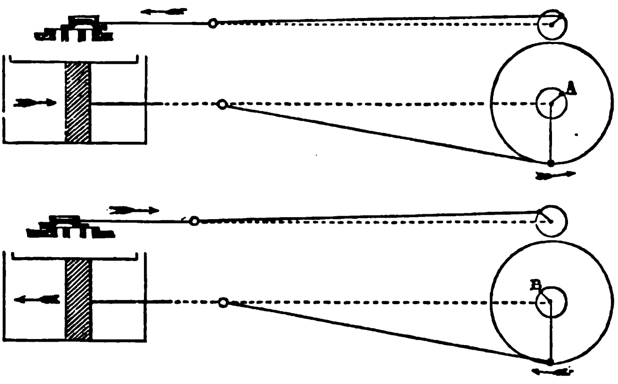
The slide-valve is connected with a point in the circumference of a small circle which represents the path of the centre of the eccentric pulley, and the piston is connected with a point in a larger circle, representing the path of the centre of the crank-pin.

The piston and valve are shown as separated in the drawing, but the small circle is repeated in the position which it actually occupies, and the method of reversal is the following:—

In the upper diagram the piston is supposed to be moving to the right, and the valve to the left; in order, therefore,

to change the motion, we must drive the piston back by admitting the steam upon the opposite side, and by letting out that portion of the steam which is urging the piston forward. Hence we must move the valve into the position

Fig. 199.



shown in the lower diagram, and shift the centre of the eccentric pulley from A to B ; the piston will then return before it reaches the end of the cylinder, and the movement of the engine will be reversed.

This explanation shows that in reversing an engine we must either shift the eccentric from the one position into the other, or else we must employ two eccentrics, and provide some means of connecting each of them in turn with the slide-valve.

The problem, as presented in the latter alternative, has been solved in a most convenient and elegant manner by an arrangement commonly known as *Stephenson's Link Motion.* (Fig. 200.)

Here A B is the starting lever, under the control of the engine-driver, and is represented as being pushed forward in the direction in which the engine is moving; C D is the *link*, provided with a groove, along which a pin can travel;

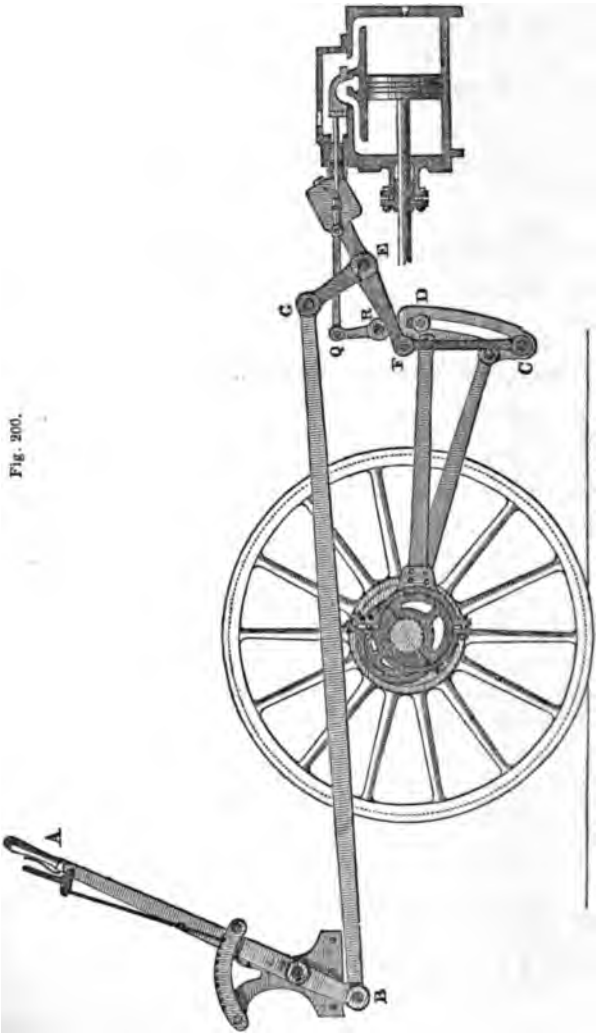


Fig. 200.

a short lever, centred at R, is connected at one end, Q, with

the slide-valve, and at the other end with the pin which moves in the link.

It is clear that so long as the pin remains near the point D, the lever centred at R will be caused to oscillate just as if the pin were attached to the extremity of the outer eccentric bar, and that the outer eccentric alone will be concerned in the motion of the valve.

If now the engine-driver wishes to reverse his engine, he pulls back the lever A B, and by doing so he raises the link C D until the pin comes opposite to the end of the inner eccentric bar: the raising of the link is caused by the motion imparted to the bell-crank lever, G E F, which is centred at the point E. A counterpoise to the weight of the link is attached to the axis passing through E at some little distance behind the bell-crank F E G, so as to be out of the way of the moving parts, and the object of this counterpoise is to enable the engine-driver to raise the heavy link and bars easily.

The inner eccentric bar now alone comes into play, and the two eccentrics being fastened to the crank axle at the angles indicated in the first part of the article, it is apparent that the valve will be shifted, and that the action of the engine will be reversed.

151. If the end Q of the connecting rod in Art. 6 be attached to a *knuckle-joint* D Q E, consisting of two bars D Q, Q E, jointed together at the point Q, we derive a combination which has been used for many purposes.

In Fig. 201 the point D is supposed to be fixed, and the point E is constrained to move in a line D R, which is perpendicular to the normal direction of C Q.

It is generally arranged that the centre of the crank shall be at such a distance from D E that the joint may straighten itself once only in a revolution of C P, and the contrivance is then applied to obtain a decreasing motion of the point E, and consequently to transmit a greatly increasing pressure.

It may be employed in this way to impart a rising and falling motion to the platten in printing machinery, and indeed the knuckle-joint, *per se*, was introduced at an early period as a substitute for the Stanhope levers.

Fig. 201.

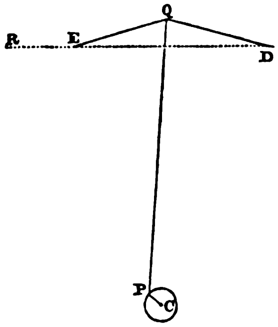
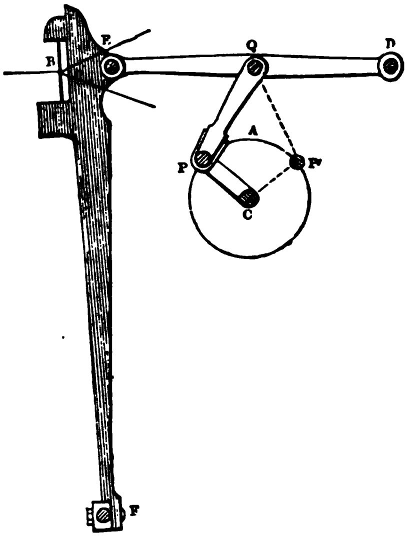


Fig. 202.



Instead of placing C at such a distance from D R that D Q E only straightens itself once during a revolution of C P, suppose that C is shifted a little in the line C Q, we shall then find that the point Q falls below D R, as well as rises above it, and there will be two positions of P on either side of A in which D Q E becomes a straight line.

Fig. 202 is intended to show the knuckle-joint as applied to a movement of this character in a Power Loom.

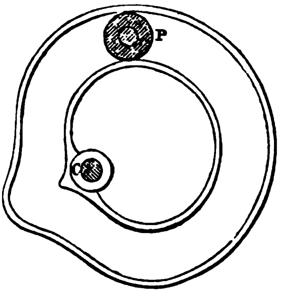
In weaving, the thread of the weft requires to be beaten up into its place after each throw of the shuttle; and in some cases, as in carpet weaving, two beats are wanted instead of one.

The combination under discussion has been used to actuate the moveable swinging frame, or batten, which beats up the weft, and the result is that two blows are given in rapid succession.

In the figure now referred to, E F is the batten, moveable about F as a centre, and it is clear that when the crank takes the positions C P, C P′, the joint D Q E will straighten, and, as a consequence, the batten will be pushed as far as it can go to the left hand, or a beat-up of the weft will take place.

By referring to Chapter I. we shall understand that a cam-plate moveable about C, and shaped as in Fig. 203, may be employed to drive the batten, and may replace the above combination, being, in point of fact, a mechanical equivalent for it.

Fig. 203.



The roller P is then connected with levers attached to the batten, and the beat-up occurs when P passes through the hollows upon each side of the projecting portion of its path upon the plate.

152. The invention of *counting wheels* is due to the celebrated Cavendish, who constructed a piece of apparatus for registering the number of revolutions of his carriage wheel, which may be seen in the Museum of George III. at King's College.

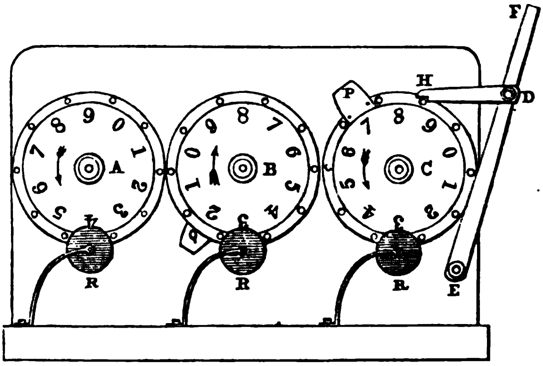
There is but one guiding principle in this branch of mechanism, however varied may be the details of the separate parts.

Each wheel of a series, A, B, C, &c., possesses ten pins or teeth, and it is contrived that one tooth only of C shall be sufficiently long to reach those of B; similarly, B is provided with one long tooth which is capable of driving A.

Thus C goes round ten times while B makes one revolution, and so on for the other wheels; in this way the series is adapted for counting units, tens, hundreds, thousands, &c.

In Fig. 204 the arm E F imparts rotation to the first wheel by the assistance of the click H D; the number registered is 988: after two vibrations of the arm the zero of C will reach the highest point, the tooth P will drive B through the space of one tooth; and the number registered will be 990; after ten more vibrations of the arm, P will again advance B, and at the same instant Q will move A,

Fig. 204.



and will bring its zero up to the highest point: the three wheels will now register 000, having passed the number 999, which is the last they can give us.

A small counting apparatus is attached to every gas meter used in houses, and registers the number of cubic feet of gas consumed; here, however, the step by step motion is not employed, the dial plates are fixed, and a separate pointer travels round each dial respectively.

The pointers are placed upon the successive axes of a train of wheels, composed of a pinion and wheel upon each axis, the number of teeth on each wheel being ten times

that on the pinion which drives it. Suppose, for example, that the pointer on the plate registering thousands completes a revolution and adds ten thousand to the score, its neighbour on the left will have moved over one division on the dial registering tens of thousands, and thus an inspection of the pointers throughout the series will at once indicate the consumption of the gas.

As we are only concerned with the counting apparatus, it is not necessary to explain the manner in which the flow of gas through the meter sets the train of wheels in motion.

Where it is intended to print the figures registered, as in the numbering of bank-notes, the step by step motion is essential, and further, each wheel must carry the letters upon its edge, and not upon the face; the apparatus employed is the same in principle as that of Cavendish, but the construction differs, the wheels being placed side by side, and close together.

One principal feature in this contrivance is the reduction in motion caused by the single driving tooth. Now, we have already seen that an endless screw is equivalent to a wheel with one tooth; we shall therefore be prepared to find that an endless screw is useful in mechanism of this character, and we meet with it in an ingenious combination known as the *differential worm wheel and tangent screw*, which may be noticed very briefly.

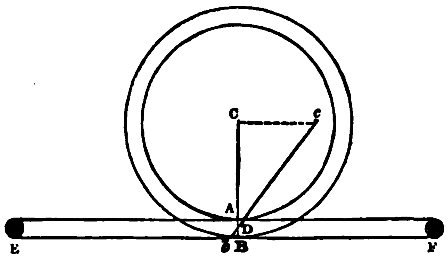
Two worm wheels, differing by one tooth in the number which they carry, are placed side by side and close together, so as to be capable of engaging with an endless screw. As the wheels are so very nearly alike, the endless screw can drive them both at the same time, and it is evident that one wheel will turn relatively to the other through the space of the extra tooth in a complete revolution, and that a very slow relative motion will thus be set up.

In this way, if one wheel carries a dial plate, and the other a hand, we may obtain the record of a very large number of revolutions of the tangent screw.

153. *Saxton's Differential Pulleys* were patented in 1832, with a view of obtaining great speed in railway carriages propelled by a rope; by the use of this invention the consumption of the rope, proposed to be wound up at a stationary engine house, would be much less than if the carriage were attached in the ordinary way.

Let two wheels of different diameters (say as 6 to 7) be centred on a common axis at C (Fig. 205) and be fastened

Fig. 205.



together, and let an endless rope be wound round the wheels and pass over pulleys at E and F in the manner shown in the diagram, the rope taking a turn round each of the pulleys.

Conceive now a pull to be exerted on the rope at B in the direction B E, then the tension of the string will cause an equal and opposite pull to rise at A in the direction A F, and thus the compound pulley has a tendency to turn about D, the middle point of A B.

This tendency in the pulley to turn about the point D causes the linear motion of C to be very much greater than that of any point in the rope; for example, when B moves through a small space, B *b*, C will advance through C *c*, which upon our supposition is thirteen times as great, so that when one yard of rope is wound up the carriage will have travelled through 13 yards.

The carriage may be at once stopped by disconnecting *the pulleys.*

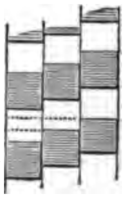
154. *Step Wheels* constitute a modification of toothed wheels; they are due to Dr. Hooke, and are used to ensure as mooth action in certain combinations of wheelwork.

It is evident that the action of two wheels upon each other becomes more even and perfect when the number of teeth is increased, but that the teeth at the same time become weaker and less able to transmit great force.

Dr. Hooke's invention overcomes the difficulty, and virtually increases the number of teeth without diminishing their strength.

Several plates or wheels are laid upon one another so as to form one wheel, and the teeth of each succeeding plate are set a little on one side of the preceding one, it being provided that the last tooth of one group shall correspond within one step to the first tooth of the next group. The principal part of the action of two teeth occurs just as they pass the line of centres, and there are now three steps instead of one from tooth A to the tooth B. (Fig. 206.)

Fig. 206.

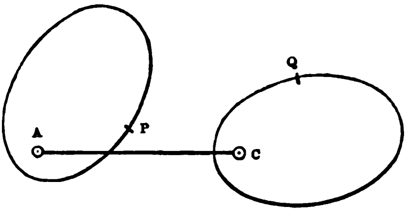


A single oblique line might replace the succession of steps, but we should then introduce a very objectionable endlong pressure upon the bearings of the wheels.

155. *Rolling Curves* have been employed to vary the relative angular velocity of two revolving pieces.

The guiding proposition connected with this subject is the following:—

Fig. 207.



Prop. Where two curved plates, centred upon fixed axes, roll together, the point of contact must always lie in the line of centres.

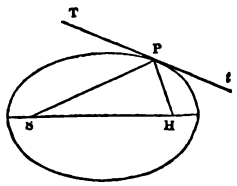
Let two such plates be centred at A and C, and suppose

that P and Q represent two points which will be in contact when the curves roll. (Fig. 207.)

Then P describes a circle round A as the plate revolves, and Q describes a circle round C; hence P and Q will come into contact whenever these circles meet each other. Now P and Q only meet once in one revolution, and therefore the circles can only meet once, i.e. they touch each other. But the circles can only touch in the line A C, therefore the point of rolling contact must lie in A C.

Cor. This is equivalent to saying that $AP + CQ =$ a constant quantity. Further than this, the curves will have a common tangent at the point where they roll upon each other.

Fig. 208.

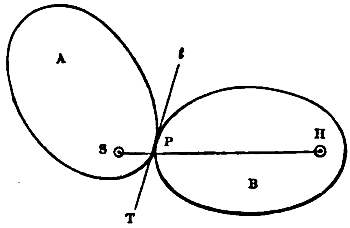


Ex. Two equal ellipses which are centred on opposite foci will roll together.

It is the property of an ellipse that the tangent at any point P makes equal angles with the focal distances S P and H P, and again that the sum of the lines S P and H P is a constant quantity. (Fig. 208.)

The two equal ellipses centred upon opposite foci are represented in contact at P. (Fig. 209.)

Fig. 209.



Let P T be the tangent to the ellipse A at P, and P *t* the tangent to the ellipse B at P.

Then $SPT = tPH$ by the property above stated, $\therefore$ T P *t* is a straight line, or the curves have a common tangent at the point P, also $SP + HP =$ a constant quantity, and the two conditions of rolling are fulfilled.

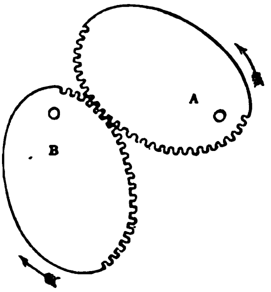
156. In practice rolling curves must be provided with

teeth upon the retreating edge, otherwise the driver would leave the follower, and the revolution would not be completed. (Fig. 210.)

As is usual in all cases where segmental wheels are employed, a guide must direct the teeth to the exact point where they commence to engage each other.

The guide may be dispensed with by carrying the teeth all round the curves: this construction is usually adopted in practice, although, strictly speaking, it destroys the rolling action entirely.

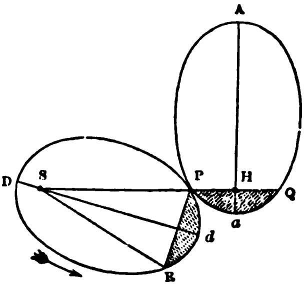
Fig. 210.



157. A quick return of the table in small planing machines is effected by the aid of rolling ellipses.

The table is driven by a crank and connecting rod, and the crank exists under the form of a flat circular plate, centred on one of the foci, and having a groove radiating from the axis as a line of attachment for one end of the connecting rod. As the plate may be set in any position upon the elliptical wheel, we propose to inquire what will be the effect of a change of direction in the groove or crank.

Fig. 211.



Let the ellipses have the position shown in Fig. 211, S and H being the centres of motion, and S P H Q being $\perp^r$ to A a, the axis of one ellipse. Draw P R $\perp^r$ D d, and let the ellipse D R d P be the driver, rotating in the direction of the arrow.

While P d R is rolling upon P a Q, the ellipse A a makes half a revolution; and

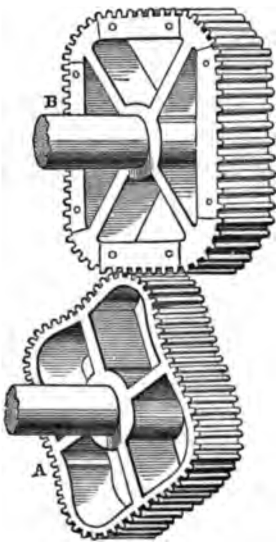
while R D P is rolling upon Q A P, it makes the remaining half revolution.

Suppose D d to revolve uniformly, then the times of a half revolution of A a will be in the same proportion to each other as the angle P S R to the angle 360 — P S R. The quick half revolution occurs when the shaded segments are rolling upon each other. If, therefore, the table be made to move in the line H S produced, and the crank be placed in a direction $\perp^r$ A a, we shall obtain the greatest possible difference between the periods of advance and return.

The practical difficulty with rolling wheels exists during that part of the revolution where the driver tends to leave the follower, and it can only be obviated by making the teeth unusually deep.

158. An instance of rolling curves is exhibited in Fig. 212, and occurred in one of the many attempts made to improve the printing press before the invention of Mr. Cowper enabled the newspapers to commence a real and vigorous existence.

Fig. 212.



The type was placed upon each of the four flat sides of a rectangular prism to which the wheel B corresponded in shape, and the paper was passed on to a *platten* corresponding in form and size with the pitch-line of the wheel A.

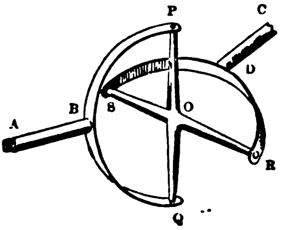
The prism and platten being in the same relative position as the wheels B and A, we can understand that the type would be in the act of impressing the paper while the convex edge of the wheel A rolled upon the flat side of B, and that in this

way we should obtain four impressions for each revolution of the wheels.

By this construction, the patentees, Messrs. Bacon and Donkin, intended to introduce the principle of continuous rotation as opposed to the reciprocating movement in a common press, and the object of imitating exactly upon the wheels A and B the form of the printing prism and of the platten, was to ensure that the paper and type should roll upon one another with exactly equal velocities at their opposing surfaces, and that no slipping or inequality of motion should destroy the sharpness of the impression.

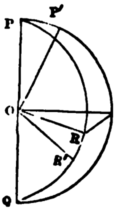
159. *Hooke's Joint* is a method of connecting two axes, whose directions meet in a point, in such a manner that the rotation of one axis shall be communicated to the other.

Fig. 213.



A B and C D (Fig. 213) represent two axes whose directions meet in the point O; the extremities of A B and C D terminate in two semicircular arms which carry a cross, P Q S R; the arms of this cross are perfectly equal, and the joints P, Q, S, and R permit the necessary freedom of motion.

Fig. 214.



As the axis A B revolves, the points P and Q describe a circle whose plane is perpendicular to A B, and at the same time S and R describe another circle whose plane is perpendicular to C D.

These two circles are inclined at the same angle as the axes, and are represented in Figure 214; thus the point P starts from P and moves in the circle P P′ Q, while the point R starts from R and describes the circle R R′ Q.

Let O P′, O R′ be corresponding positions of the two

arms; the P′ R′ is constant, but changes its inclination at every instant, and as a consequence the relative angular velocities of O P′ and O R′ are continually changing.

To find the relative angular velocities of the axes A B and C D, we proceed as follows:—

Let the circle *p r q* (Fig. 215) represent the path of P, *p t q* being the projection upon this circle of the path of R, and suppose θ to be the angle between A B and C D; then the dimensions of the curve *p t q*, which will be an ellipse, can be at once deduced from the equation O t = O r cos θ.

Draw R *m* $\perp^r$ O *r*, then R *m* will be the actual vertical space through which R has descended while O P describes the $\angle$ *p* O P. But the path of R is really a circle, and only appears to be an ellipse by reason of its projecting upon

Fig. 215.

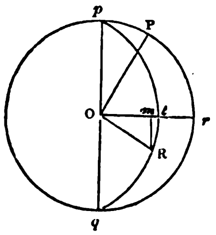


Fig. 216.

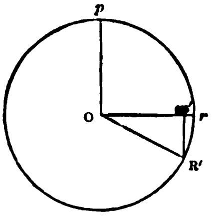
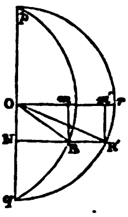


Fig. 217.



a plane inclined to its own plane; in order, therefore, to estimate the actual angular space through which O R has moved, we must refer this motion to the circle which R really describes (Fig. 216), and thus by making R′ *m*′ = R *m*, we shall find that *m*′ O R′ will be the angle which O R describes while O P moves through the angle *p* O P.

We may represent the motion of both axes upon one diagram by combining the ellipse *p* R *q* with the circle *p r* R′; if we then draw N R R′ $\perp^r$ *p* O *q* and join O R, O R′, it will be easy to see that the angles R O *r*, R′ O *r*, are those described in the same time by the axes A B and C D. (Fig. 217.)

Hence the axes A B, C D revolve together, but unequally, and the angles which they describe in the same time will be at once apparent upon referring to the positions of O R, O R′ at any period of the motion.

Furthermore, O R and O R′ coincide when R is at the end of an axis of the ellipse *p* R *q*, an event which happens four times as the cross goes round once, and there is therefore this curious result, that however unequal may be the rate at which the axes are at any time revolving, they will nevertheless coincide in relative position four times in one revolution.

Dr. Hooke's universal joint may often be very useful in light machinery which is required to be moveable, and the parts of which do not admit of very accurate adjustment; but it will be understood that the friction, and especially that irregularity which we have just proved to exist, would render it necessary to confine the angle between the shafts within narrow limits in actual practice.

THE END.

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